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ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT

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AGARD ADVISORY REPORT No. 166

Rotorcraft Icing - Status and Prospects

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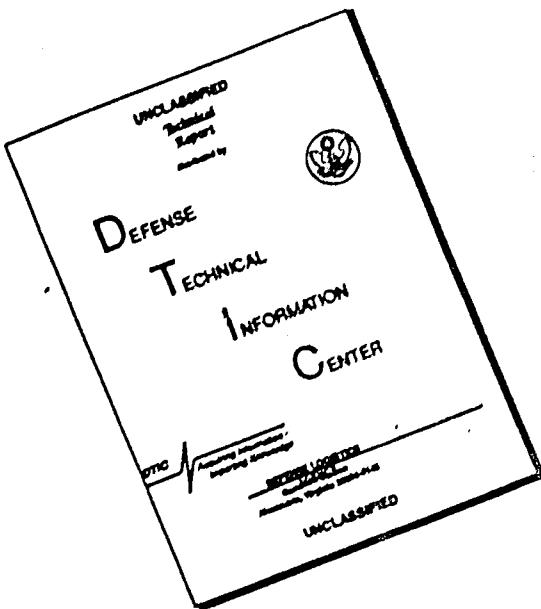
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NORTH ATLANTIC TREATY ORGANIZATION
ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT
(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

AGARD Advisory Report No.166

ROTORCRAFT ICING –

STATUS AND PROSPECTS

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- Rendering scientific and technical assistance, as requested, to other NATO bodies and to member nations in connection with research and development problems in the aerospace field;
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PREFACE

The fielding of a new generation of helicopters in the NATO countries promises to provide significantly increased adverse weather operational ability. As military instrument flight operations increase, the probability of icing encounters will also rise. Unfortunately, neither the technology nor the resources required to provide complete helicopter ice protection are available for application to NATO helicopters of the 1980's. Therefore, it was deemed appropriate for the Flight Mechanics Panel (FMP) of the Advisory Group for Aerospace Research and Development to sponsor a Working Group #09 to address the following subjects:

- Develop a consensus on the icing protection requirements for the NATO operational environment in the technical terms necessary to define system design criteria.
- Make an assessment of potential technical approaches to improved helicopter airframe and rotor icing protection.
- Make recommendations on specific research and development priorities.
- Make recommendations on the exploitation of existing facilities and the development of new facilities for icing research and simulation.
- Identify opportunities for cooperative efforts among the member nations.

The Working Group formed five subgroups, each studying a main theme:

- Operational Environment, Meteorological Conditions and Weather Forecasting.
- Technology Base for Icing Instrumentation and Mathematical Modelling.
- Facilities for Development and Clearance.
- Ice Protection System Technology.
- Proposed Standard Requirements and Procedures for Icing Clearance.

Four meetings of the entire Working Group were held at MOD, London, United Kingdom, 29-30 May 1979; ONERA, Chatillon-sous-Bagneux, France, 10-12 September 1979; Hampton, Virginia, United States, 22-24 April 1980; and AGARD Headquarters, Paris, France, 3-5 November 1980. Each meeting included formal information exchange for the entire Working Group as well as subgroup sessions to plan, develop and review the ensuing report. The Working Group structure provided excellent and valuable cross-fertilization of information and concerns. This report should provide a thorough background to those not already familiar with the subject of Rotorcraft Icing. More importantly, it provides a number of recommendations which should be addressed by both operational and technical communities of the NATO member nations.

The membership of the Working Group is listed below; certain members, as indicated, were charged with the preparation of the various chapters of this report, using the material assembled by the whole Group.

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Special appreciation is extended to Mr. Edward S. Carter, Jr., who developed initial plans for this Working Group and served as its Chairman during the first two meetings. Thanks are also due to a number of people, not members of the Working Group, who have contributed material for this report through the Chapter editors, and to Mr. Trevor Wilcock, Executive of the AGARD Flight Mechanics Panel, for his outstanding assistance during the course of the Working Group's activities.

RICHARD B. LEWIS II
Chairman, Working Group on Rotorcraft Icing;
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SUMMARY

The AGARD Flight Mechanics Panel Working Group on Rotorcraft Icing held four meetings during 1979 and 1980 to examine the impact of icing meteorological conditions on helicopter operations, to assess potential technical approaches for improving ice protection, to recommend specific research and development priorities, and to discuss opportunities for future cooperative efforts among member nations. The Working Group formed five subgroups whose reports are contained in the following chapters. The principal findings of the Working Group are as follows:

1. Operational Environment, Meteorological Conditions and Weather Forecasting.

Helicopter icing is a significant operational consideration for helicopters operating throughout Europe. Existing weather statistics demonstrate significant operational limitations during the winter months, and for as much as five percent of the time, on a year-around basis, icing can occur at operational altitudes over central Europe. Unfortunately the existing meteorological data base is insufficient to describe the operating environment in which NATO rotorcraft must conduct flight. This stems from two factors 1) earlier icing data concentrated on altitudes for fixed wing aircraft operations, which are generally higher than rotorcraft operational altitudes and 2) only limited examination of the icing environment over Europe has taken place with modern instrumentation and data reduction. At present for design purposes, the United States Federal Air Regulation 25 Appendix C or the UK Icing Atmosphere are employed for determination of airworthiness release of helicopters. However, neither of these atmospheres adequately defines the operational environment. This condition is exacerbated by the fact that forecasting techniques are currently inadequate to allow unrestricted helicopter operations in icing conditions. In order to ameliorate the above conditions, increased coordination among cloud physicists, forecasters, and helicopter icing specialists is urgently needed - and ultimately a new icing atmosphere is required to better define the helicopter operational icing requirements. Data on freezing rain, freezing fog, snow and mixed liquid and crystal conditions need to be added to the present inventory of classical icing information so as to allow a thorough understanding of adverse weather operating conditions.

2. Technical Base for Icing Instrumentation and Mathematical Modelling

The Working Group found that insufficient attention had been paid to understanding the fundamental mechanisms of ice accretion and shedding from rotor airfoils. It is felt that a significant opportunity exists to exploit a combination of two-dimensional and three-dimensional model scale testing, measurement of ice release mechanisms, inclusion of heat transfer models, and consideration of icing simulation. These efforts should be aimed at development of analytical models verified by both laboratory and full-scale data which then can be used to better predict performance of rotors in icing conditions. Only with the above analytical basis can ice accretion and shedding characteristics become sufficiently predictable to permit the determination of what type of ice protection is necessary or, conversely, what degree of flight envelope release might be permitted with a given level of ice protection. In addition to the ice accretion on main rotors, there are opportunities for further improvement in research and development of operational icing sensors, these being necessary to complement the ice protection systems on board rotorcraft.

3. Facilities for Development and Clearance

A major product of the Working Group was to compile a detailed catalog of all NATO icing test facilities. This examination gave rise to several concerns on the part of the Working Group to include the observation that the Canadian National Research Council's small high speed icing tunnel is a one-of-a-kind facility that needs to be available to support the analytical development recommended in the previous paragraph, and that the tunnel should be reactivated or replaced. Similarly, the Working Group found that the Canadian NRC Ottawa Spray Rig is a useful development facility for helicopter icing and should be maintained in operation. As a result of dialogue between the Working Group and the Canadian authorities, a decision has been made to retain the Ottawa Spray Rig in operational status for the near future. Efforts underway at the NASA-Lewis Research Center regarding rehabilitation of the Icing Research Tunnel and considering a major new icing test facility are strongly endorsed. The US Army Helicopter Icing Spray System Improvement Program is also strongly supported by the Working Group and, as a recommendation for future discussion, the need for European airborne icing spray systems should be considered. A conclusion reached by the Working Group is that current full-scale development and qualification facilities and procedures are extremely expensive and time-consuming. It is clear that, once development and qualification are underway, tests in natural icing conditions are invariably required, and these introduce very significant costs for the clearance of helicopter systems for flight in icing conditions. The opportunity exists to greatly improve analytical modelling of rotorcraft icing to assist in development and clearance and thereby reduce the time and cost required.

4. Ice Protection Systems Technology

The Working Group has examined all current deicing systems technology concepts and these are discussed in the report. The general conclusion of the Working Group is that electrothermal deicing systems are the only effective present system for broad application. However, it is noted that the cost of electrothermal deicing in terms of weight, power and expense is high, and provides an incentive for examination of alternatives. Therefore, additional work is clearly warranted on options such as ice phobics, fluid ice suppressant systems, pneumatic boots, vibratory surface systems, microwave and other hybrid systems concepts. The Working Group also found that the opportunity exists now, with a new series of ice-protected aircraft such as the Black Hawk and Puma, to conduct careful exploration of operational limitations with the ice protection systems deliberately turned off, so as

to simulate an aircraft without (or with inoperative) ice protection. Only through such definition of the actual icing environment can a better estimation be made of the operational impact of icing conditions on helicopter flight operations.

5. Proposed Standard Requirements and Procedures for Icing Clearance

One of the most significant products of the Working Group was to draft and coordinate amongst the authorities in France, the United Kingdom and the United States a set of proposed standard requirements and procedures for icing clearance. It is felt that this clearance procedure constitutes a basis for NATO-wide icing clearance and should be adopted by the NATO military community as an interim approach. The opportunity also exists to consider this proposal for civil icing clearance. However, it is recognized that there are certain civil missions where the peculiarities of the route structure, operational altitudes, and other considerations introduce different requirements for helicopter icing clearance. Finally, it is urged that a coordinated effort may be made to obtain data from operational experience with the new generation of cleared helicopters in order to further validate and refine the icing clearance procedure.

6. Recommendations for Future Activity

The Working Group feels strongly that helicopter icing will remain a major operational consideration for the NATO community in the foreseeable future. Accordingly, follow-on activities to assess the progress being made in helicopter icing analyses and modelling, as well as the work underway to improve definition of helicopter icing atmospheres and to compare operational experience in ice protected helicopters, need to be undertaken. The opportunity also exists for the NATO Army Armaments Group AC/225 Panel X Helicopter Icing Sub-Group to initiate a helicopter icing data collection program for the consolidation and dissemination of operational experience and for NATO AC/225 Panel XII (Meteorology) to vigorously address the issue of atmospheric environment likely to be encountered during NATO helicopter operations.

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1. OPERATIONAL ENVIRONMENT, METEOROLOGICAL CONDITIONS AND WEATHER FORECASTING

1.1 BACKGROUND

There are currently more than 5,000 military and civilian helicopters operated in the NATO countries. They perform a variety of missions including attack, scout, cargo, utility, antisubmarine warfare, scheduled passenger carrying, and offshore logistics. At present nearly all of these helicopters lack onboard instrumentation to quantify a given icing environment or necessary rotor ice protection equipment. Only a few of these vehicles are cleared for operation in even light icing. Consequently, when significant icing conditions are forecast or inadvertently encountered, helicopter operations must be modified.

A substantial folklore concerning the effect of icing on helicopters has developed amongst the operational community based on individual icing encounters. This has given rise to two divergent bodies of opinion which either regard icing conditions as a complete bar to helicopter operations or as an overstated hazard. There exist, however, numerous well-documented reports which relate extreme loss of performance, excessive vibrations, engine loss, incidental damage from shed ice, etc., for a wide variety of helicopters.

In the late 1960s the qualification agencies and development firms in France, Germany, the United Kingdom and the United States began testing modern electrothermal rotor deicing systems in both artificial and natural icing conditions. This test experience was obtained much more slowly than desired by military and civil users, and considerable pressure was brought to permit limited icing clearances for unprotected helicopters. By the early 1970s the technical community had generally concluded that operation of unprotected rotor systems in known or forecast moderate icing conditions entailed unacceptable risk, and operational users were challenged to define both the operational environment in which they desired to fly and the price they were willing to pay for that capability. Most users concluded that the cost of retrofitting electro-thermal ice protection to existing helicopters was excessively costly, and attention was focused on the emerging new developments including the PUMA, the BLACK HAWK, the Advanced Attack Helicopter, and the modernized Chinook. During the late 1970s the United Kingdom cleared the Sea King and Lynx for limited operations in icing conditions without rotor ice protection.

At the present time there are only a few hundred operational rotocraft within NATO equipped for operation in icing conditions. Efforts are still underway to provide the same capability (at minimal cost) for many of the remaining NATO helicopters. Towards that end, it is necessary to understand the meteorological conditions which bring about helicopter icing, the ability to forecast (and avoid) excessive icing encounters, how to measure icing conditions once encountered and the range of operational options which result from helicopter icing.

Icing is the accumulation of ice on aircraft during flight and is one of the most significant meteorological hazards for air vehicles. It occurs when the surface temperature of an aircraft is below freezing and the atmosphere contains supercooled water droplets. Supercooled water droplets usually are to be found down to -12°C but very seldom at lower temperatures due to the formation of ice crystals and therefore precipitation (Bergeron-Findeisen Theory). See Figure 1-1. Three different types of ice are to be considered: rime ice, clear ice, and frost.

The icing intensity depends on several parameters:

- Air Temperature (OAT): Temperatures of greatest concern for helicopter icing are approximately -5°C to -15°C .

- Liquid water content (LWC): Increasing liquid water content is generally accompanied by increasing icing severity although no direct correspondence has been established for helicopter rotors. For fixed surfaces, the rate of icing accumulation is directly proportional to LWC.

- Droplet size and distribution: Droplet size and distribution affect the catch efficiency of aircraft surfaces and therefore icing intensity. With increasing droplet size and increasing temperature, the amount of immediate freezing water of these droplets decreases. That means: more water remains liquid, forming clear ice and run back.

- Catch efficiency for droplets: Thin profiles catch more droplets than thick ones; large droplets impinge more often than smaller ones.

- Kinetic heating: Boundary layer heating causes faster moving surfaces to increase in temperature thus delaying accumulation of ice. This is particularly noticeable on the outboard portions of rotor blades.

Generally icing occurs in supercooled clouds. Clouds are formed when air containing water vapor rises, expands under the lower pressures which exist at higher levels in the atmosphere, and thereby cools until some of the vapor condenses into a cloud composed of myriads of tiny water droplets. This usually happens in frontal systems and convection clouds. Cooling can be affected also by radiation (low stratus) and mixture (sea fog). The icing intensity is principally affected by the liquid water content.

Droplet size, droplet distribution and temperature also influence icing conditions, especially the type of icing to be encountered and the degree of ice adhesion on rotating components. Small droplets with low temperature cause RIME ICE, large droplets with higher temperatures cause CLEAR ICE.

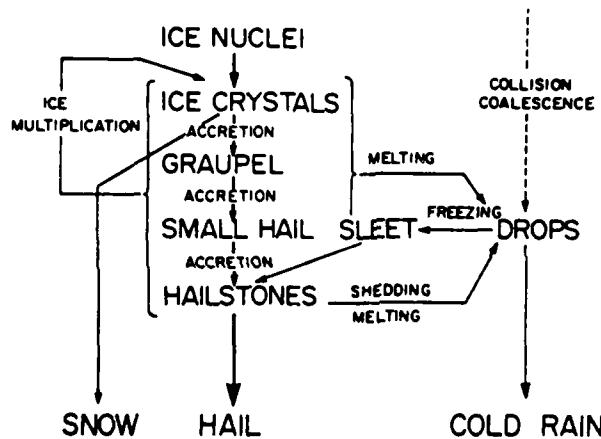
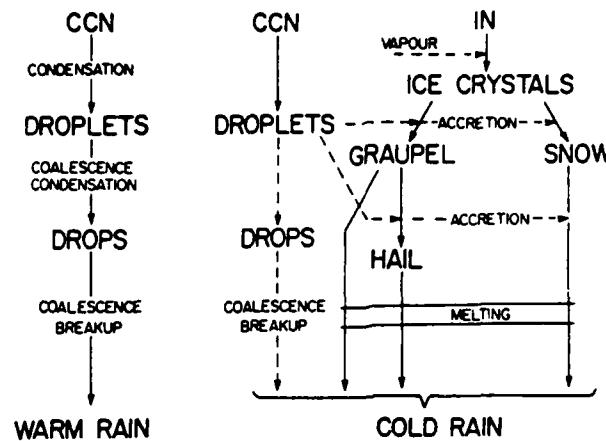


FIGURE 1-1: DEVELOPMENT OF WARM AND COLD RAIN BY CLOUD CONDENSATION NUCLEI AND ICE NUCLEI.

Therefore the following parameters are of major interest:

- a. Flight parameters:
 - altitude
 - true airspeed
 - location in cloud
 - time in cloud
- b. Meteorological parameters:
 - outside air temperature (OAT)
 - total water content (vapour, liquid and solid)
 - droplet size and distribution
 - relation of the horizontal extent of a cloud to the extent of the icing zones contained in it.

For operational purposes it is essential to understand all of the parameters listed above and to plan flight operations such that the atmospheric conditions encountered do

not exceed the level of clearance for the aircraft in question. For development and qualification test purposes, it is necessary to locate large stable areas where cloud conditions and temperatures permit testing of a range of icing conditions.

During icing tests in natural conditions, four types of clouds are sought:

- 1) frontal thick stratoform clouds (stratus and nimbostratus)
- 2) frontal extended stratocumulus
- 3) post-frontal cumulus clouds: cold air clouds including cumulus, altocumulus and some cumulonimbus
- 4) freezing fog created by temperature inversions near the ground

1.2 METEOROLOGICAL CONDITIONS

1.2.1 Central Europe Icing Areas

Figure 1-2 shows the average height of freezing level in certain airmasses over Central Europe. It is seen that freezing levels below FL 100 (700 mbar) occur throughout the year. Figure 1-3 from reference 1-1 shows the percentage probability of temperatures equal or below zero degrees centigrade combined with broken/overcast cloud cover. Icing in frontal systems can occur all over the year in those parts of Europe where helicopter flight operations are conducted. USAF Technical Report 220 (reference 1-2) shows that icing most often occurs between October and April. The probability of occurrence is increased in the north and decreases in the south and east in summer, and in the south and west in winter.

The combined action in the Atlantic Ocean, Mediterranean Sea, and the major mountain ranges create periodical frontal situations, the most typical of them being:

- "Western fronts," consisting of masses of humid air coming from the Atlantic Ocean, partially modified by the presence of Massif Central and Morvan mountains which result in icing all along the central axis of France, from south to north
- "Northern fronts," consisting of cold air coming from the North Sea, contain less water than the western ones, but often more concentrated in stratocumulus clouds.

1.2.2 Icing in Frontal Systems

Icing zones in frontal systems are shown in Figures 1-4 and 1-5. Figure 1-6 shows the most important traces of low pressure systems over Europe. Vertical motion of rising air in a warm front is very slow, about 10^{-1} m/sec, so in warm fronts there usually is enough time to form ice crystals and precipitation (see Figure 1-4). LWC remains almost always less than 1 g/m³ but for very long distances of some 100 km. The extent of a cold front is about 100 km with embedded convective clouds.

1.2.3 Icing in Convective Clouds

Vertical motion in cumulus clouds goes up to 10 m/sec with more than 20 m/sec in cumulo nimbus. So LWC can rise up to more than 2 g/m³ with more than 20 g/m³ in cumulo nimbus. Their horizontal extent depends on whether they are formed in an unstable airmass or in a frontal system (usually cold front) and on the grade of instability. Unfortunately increasing stability affects larger clouds from some 100 m in diameter up to 10 km for thunderstorm cells.

1.2.4 Icing in Low Stratus

Low stratus is formed by radiation of a surface. In hilly regions the formation of cold air below an inversion layer normally affects a motion of this air (valley breeze), and stratus layers are not stable. Lingering low stratus usually occurs in flat areas or valleys. While, along the coast and over sea, fog is often affected by mixing conditions, it very often occurs in areas separated from the coast during high pressure influence. In low stratus there usually exists vertical motion. While radiating (cooling) on the top there is also some heating from the surface below. So, in the low stratus layer there is an unstable gradient which forms cells of vertical motion. They are very close together and about 1000 m in diameter. A continuous up and down-wards motion of air and moisture makes cloud particles grow and shrink, ice particles are formed on ice nuclei and fall out of the cloud as precipitation. But after about one day all ice nuclei have disappeared, the cloud droplets can grow during ascent until they are heavy enough to fall. During descent they continue growing by coalescence. On the base of the low stratus these large droplets of 30-100 mm are to be observed as freezing fog, forming heavy clear ice.

1.2.5 Freezing Rain

Freezing rain occurs when a warm front is moving over a cold layer near a surface. Precipitation, formed in the frontal clouds as snow, falls, melts at altitudes where the temperature is above freezing and drops as rain below an inversion into the cold layer, forming clear ice. The liquid water content during freezing rain depends on the

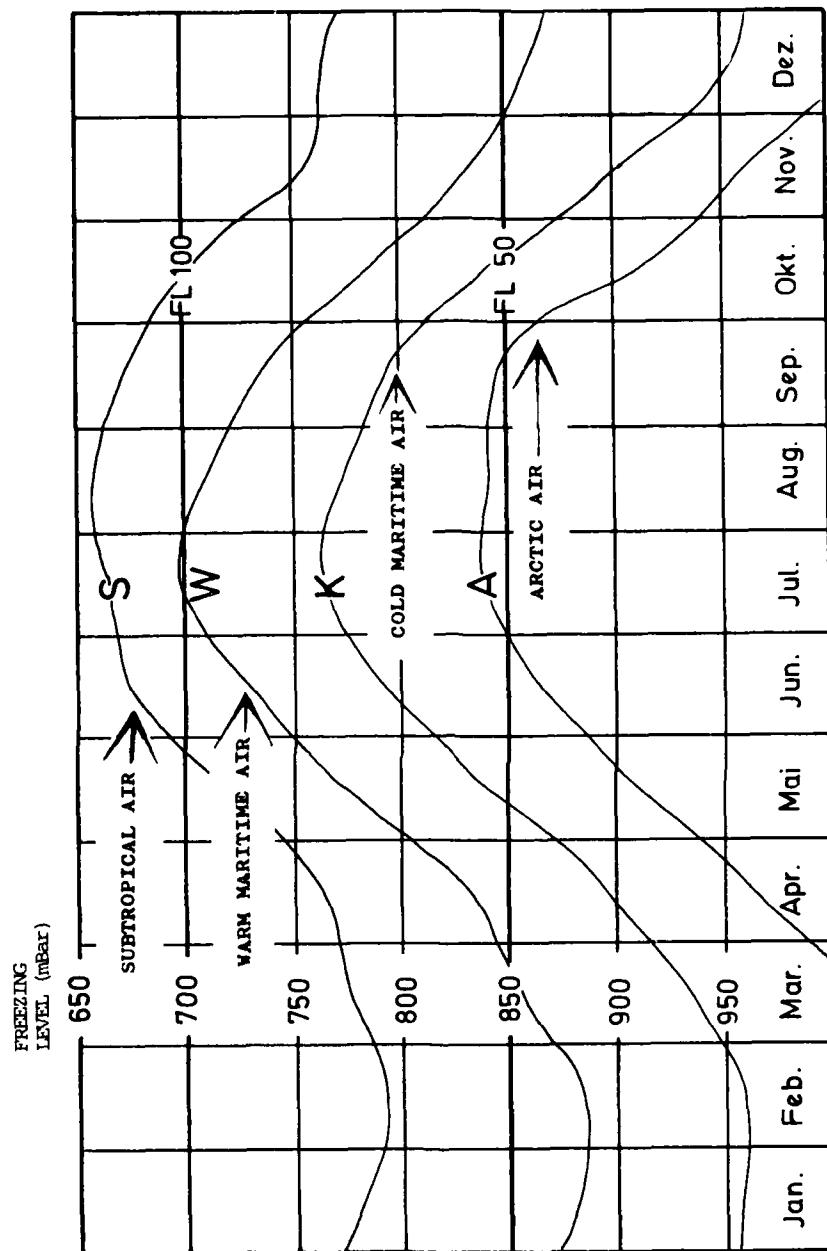
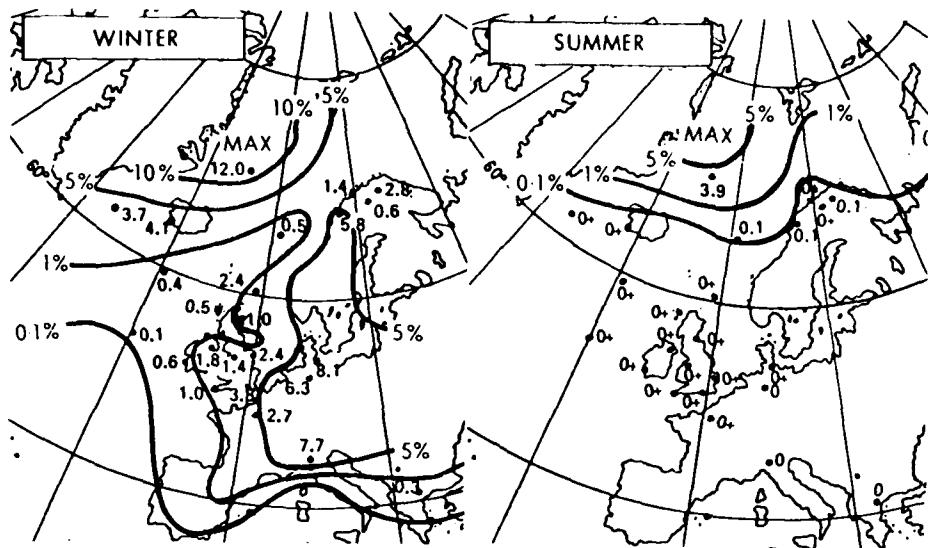


FIGURE 1-2. AVERAGE ALTITUDE (IN mBAR) OF THE FREEZING LEVEL IN VARIOUS AIRMASSES OVER CENTRAL EUROPE

PERCENTAGE PROBABILITY OF TEMPERATURE $\leq 0^{\circ}\text{C}$
COMBINED WITH MORE THAN HALF COVER OF CLOUD (AVERAGED 0-1000FT)



PERCENTAGE PROBABILITY OF TEMPERATURE $\leq 0^{\circ}\text{C}$
COMBINED WITH MORE THAN HALF COVER OF CLOUD (AVERAGED 2000-5000FT)

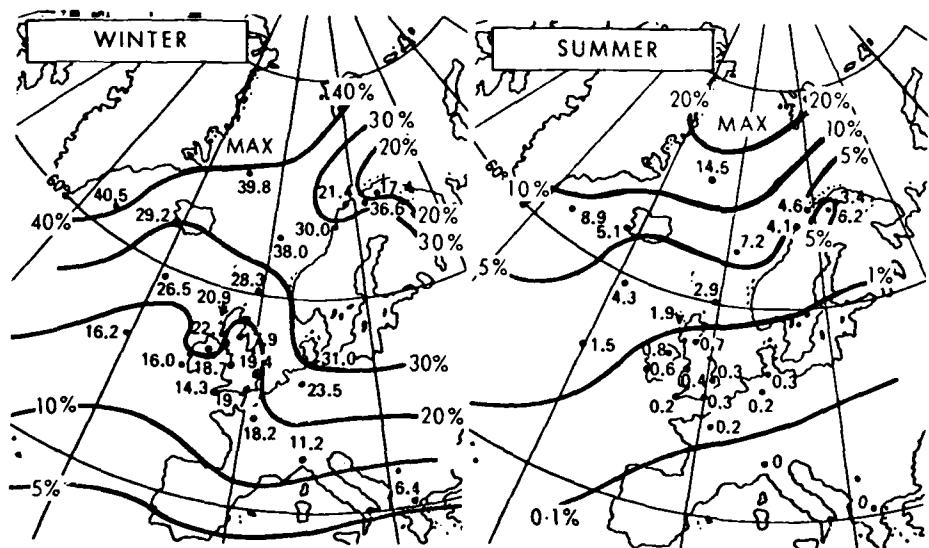


FIGURE 1-3: PROBABILITIES OF FREEZING TEMPERATURES AND CLOUD COVER
OVER WESTERN EUROPE. (From Ref 1-1)

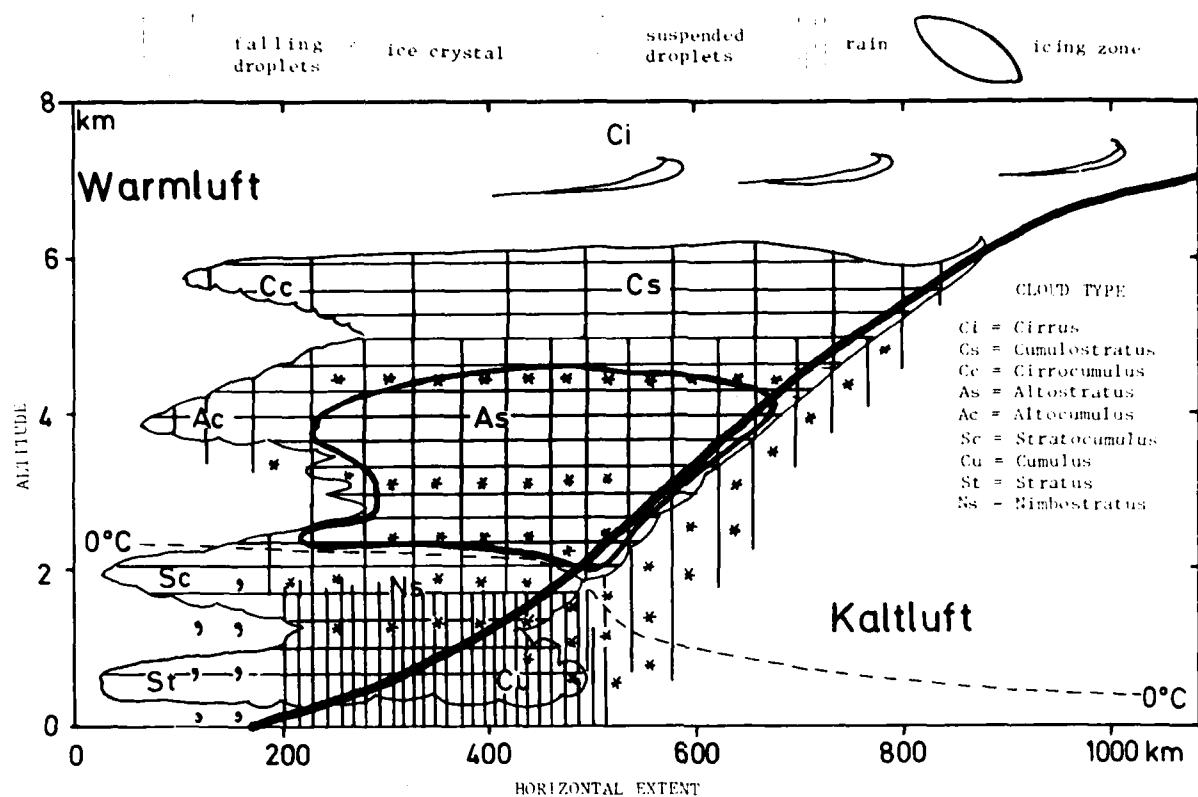


FIGURE 1-4: ICING ZONE IN A WARMFRONT

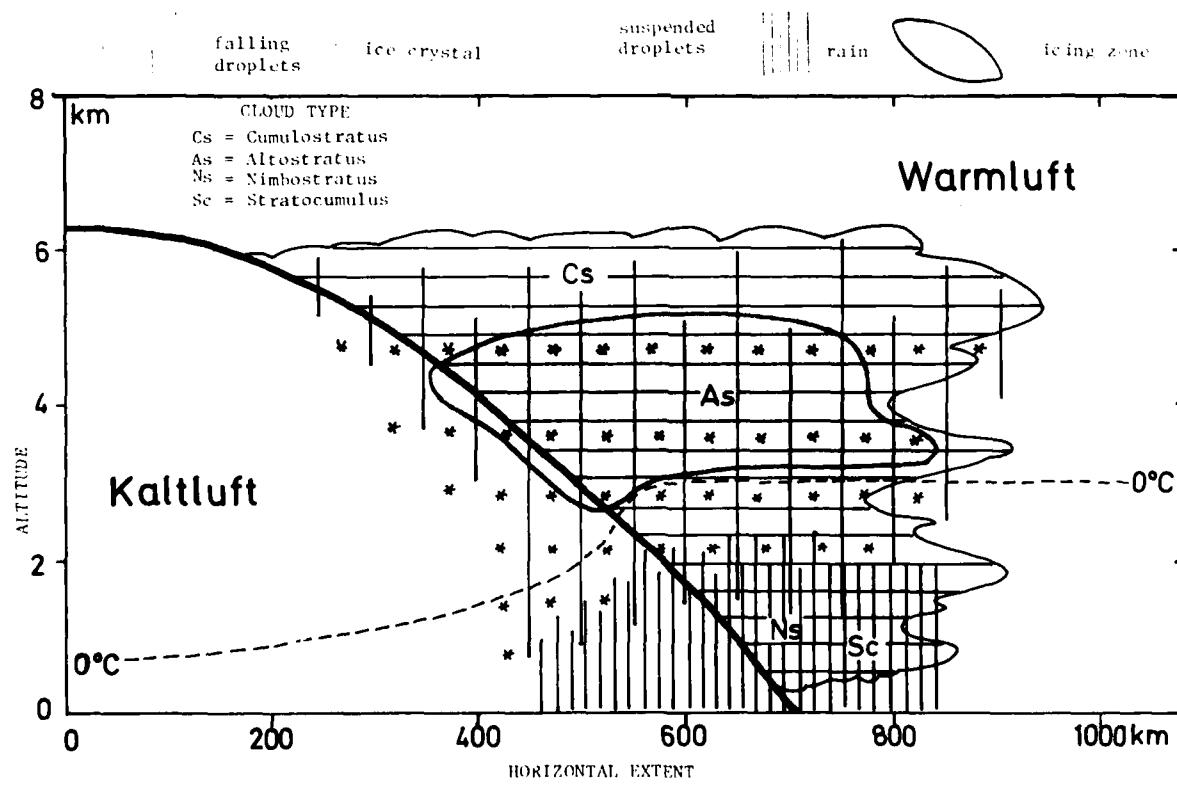


FIGURE 1-5: ICING ZONE IN A COLDFRONT

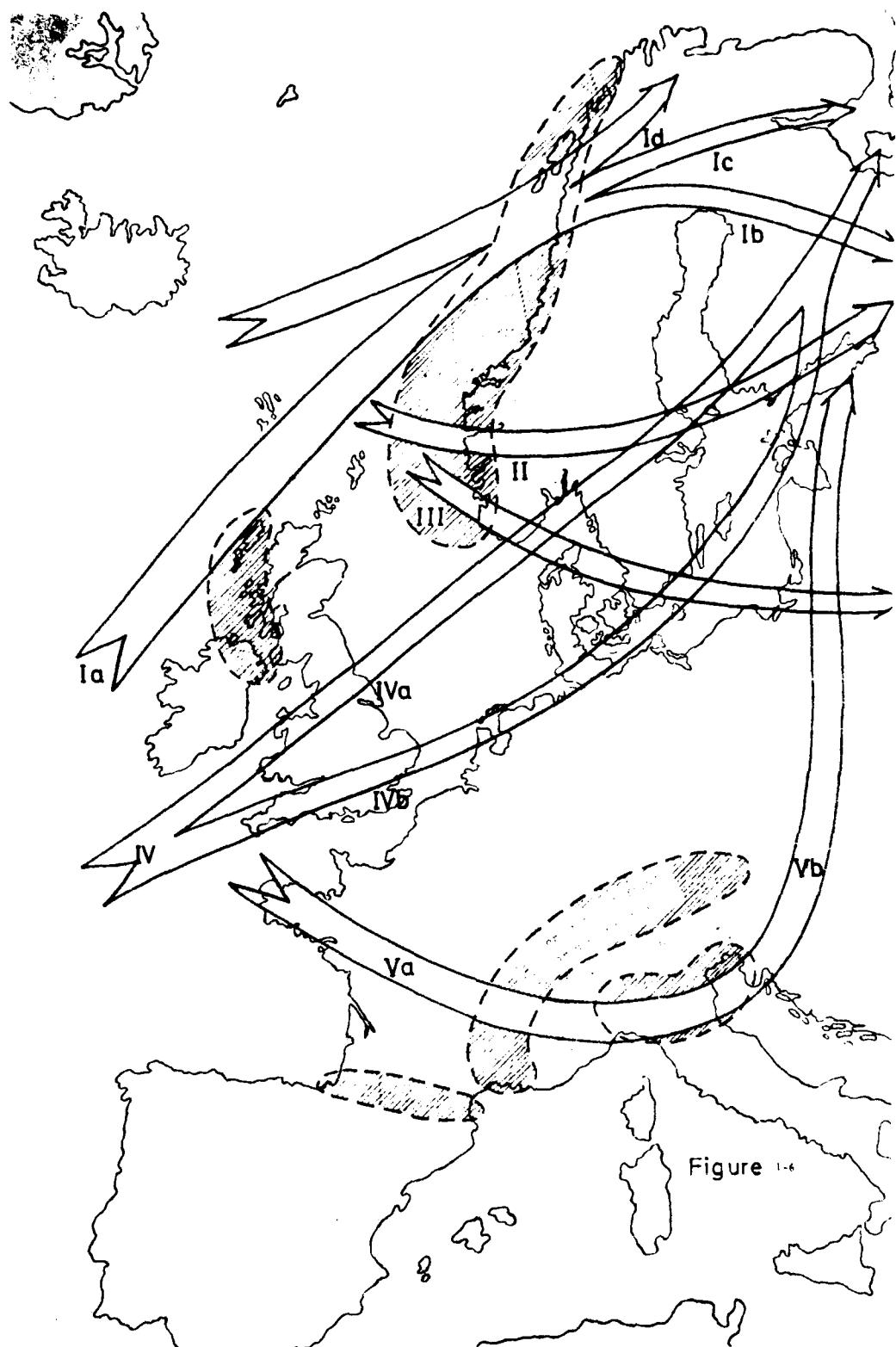


FIGURE 1-6: TYPICAL FRONTAL PASSAGES OVER WESTERN EUROPE.

intensity of rainfall. The meteorological condition "moderate rain" means: less than 4 mm rain per hour. Rain drops of a diameter of about 0.5×10^{-3} m fall at about 3 m/s. So, the water content of moderate freezing rain is at the most 0.37 g/m, which is rather small.

1.2.6 Orographic Areas

There are certain areas to be found with more or less orographic lifting and upslope, especially adjacent to mountains. Their location and intensity depends on windspeed, wind direction, temperature and moisture. Figure 1-6 shows only the most important upslope areas, influenced by the Alps, the Scottish Highland, Norwegian Mountains and the Pyrenees.

1.3 QUALITATIVE INFLUENCE OF ICING CONDITIONS ON HELICOPTER OPERATIONS

In an attempt to better determine the influence of icing conditions on helicopter operations, both military and civilian operators were queried.

German CH-53 operational sites located in Southern Germany, which is a hilly region between 100 and 1500 m MSL and an alpine region up to 3000 m MSL, report that between October and March about 20 percent of all flights have to be cancelled or altered because of predicted icing. There are 5 percent cancellations between April and September. The operational impact of various forecast situations is as follows:

- Frontal systems: When icing is expected during an IFR-flight, then they try to change into VFR-flight in low level. This can be done in 50 percent of the cases.
- Low stratus: No limitation if destination/alternate are out of low stratus area. This happens in about 50 percent of cases.
- Freezing conditions: No flights are conducted.
- Falling snow: No IFR-flights in temperature range -4° to $+4^{\circ}$ C.

U.K. civil operators, oversea. The percentage probability of icing encounter over North Sea and Norwegian Sea at altitudes of 1000 ft and 5000 ft were derived by the U.K. Meteorological Office in the early 1970s for use in definition of WG 34 icing flight requirement. Data covering a much larger geographical area are given in USAF Air Weather Service Technical Report 220 (ref 1-2). This report is an update of the methodology used within the AWS to determine the climatological probability of aircraft icing throughout the Northern Hemisphere. It presents isopleth charts of the 1000-, 850-, 700- and 500 mb surfaces for each of the twelve months. A station listing and locator chart gives the extensive areal coverage of the data used in the computerized calculations.

KLM civil helicopter operational data are shown in Table 1-1. Flight cancellations on an annual basis reach only 2.4% even for the bad winter of 1978/79, though on a monthly basis as many as 16% of flights are cancelled. Of these, around 50% would still have been cancelled due to other weather factors even if the helicopters had been approved for operation in icing conditions. It should be noted that these statistics are for unscheduled operations, where a particular flight can be rescheduled rather than cancelled. For scheduled operations the cancellation rate might be somewhat higher.

Summary of operational icing conditions. Since helicopter flight operations are conducted from the Arctic (i.e., Spitzbergen/Svalbard close to 80° N latitude) to the Mediterranean Sea, over both land and sea, icing conditions can occur over parts of Europe nearly all year. To precisely determine the percentage of flights which must be altered because of icing conditions is very difficult due to:

- different icing intensities
- different types of helicopter with
- different missions at
- different altitudes and temperatures
- different assessment of icing influence to the helicopter by the pilot
- different forecast techniques and knowledge
- different time of endurance and
- different frequency of flights

In addition it is very difficult to define icing areas and icing zones and their frequency of occurrence. To characterize the percentage probability of icing in very rough terms, one can combine (see Figure 1-3) the percentage probability of temperature equal to or less than 0° C with more than 4/8 cloud over Western Europe. This yields:

	Winter	Summer	Average
Maximum	10%	40%	25%
Minimum	0%	10%	5%

or an average overall of 15 percent (between 2000 and 5000 feet) probability of the

occurrence of icing clouds. In addition, experiences out of more than 50 intentional test flights in forecast icing conditions reveal that icing occurred only one-third to half of the time in clouds. Therefore 5 percent is a nominal probability of icing encounter over land, with a maximum of about 8 percent over Northern Europe and 2 percent as minimum over Southwestern France. Over the straits of Greenland, as many as 15 percent of flight operations will result in icing encounters.

TABLE 1-1
KLM HELICOPTER OPERATIONAL EXPERIENCE

	ICING %	VISIBILITY %	GENERAL %	TOTAL %	NUMBER OF FLIGHTS PLANNED
JAN 1977	- -	1 0.4	- -	1 0.4	232
FEB	- -	3 1.2	- -	3 1.2	249
MAR	- -	3 1.0	- -	3 1.0	288
APR	- -	- -	- -	- -	284
MAY	- -	- -	- -	- -	279
JUN	- -	5 1.8	- -	5 1.8	274
JUL	- -	- -	- -	- -	286
AUG	- -	4 1.2	- -	4 1.2	335
SEP	- -	- -	- -	- -	307
OCT	- -	18 5.7	- -	18 5.7	317
NOV	3 1.0	1 0.3	- -	4 1.3	305
DEC	11 3.7	4 1.4	- -	15 5.1	296
JAN 1978	- -	3 0.9	- -	3 0.9	324
FEB	15 6.2	9 3.7	- -	24 9.9	242
MAR	- -	7 2.4	- -	7 2.4	288
APR	- -	10 4.1	- -	10 4.1	245
MAY	- -	6 2.0	- -	6 2.0	294
JUN	- -	10 2.8	- -	10 2.8	361
JUL	- -	2 0.6	- -	2 0.6	337
AUG	- -	1 0.3	- -	1 0.3	349
SEP	- -	- -	- -	- -	334
OCT	- -	7 2.0	4 1.2	11 3.2	343
NOV	5 1.6	40 12.8	13 4.1	58 18.5	313
DEC	7 2.8	- -	15 6.0	22 8.7	252
JAN 1979	20 8.2	3 1.2	14 5.7	37 15.1	245
FEB	43 16.0	19 7.1	28 10.4	90 33.5	269
MAR	11 4.2	6 2.3	1 0.4	18 6.8	263
APR	1 0.4	- -	2 0.8	3 1.3	237
MAY	- -	4 1.4	3 1.1	7 2.5	278
JUN	- -	12 4.3	3 1.1	15 5.4	278
JUL	- -	1 0.4	8 3.3	9 3.7	244
AUG	- -	3 1.0	1 0.3	4 1.3	299

Even less data exist on flight in freezing rain, freezing fog, snow and mixed (liquid and crystal) conditions. An indication of French experience with the ice-protected PUMA helicopter is shown in Figure 1-7. In general, the design criteria for these conditions are not well established, nor are adequate forecasting techniques available. This area remains one for further research and experimentation.

1.4 METEOROLOGICAL DATA COLLECTION AND FORECASTING

As stated earlier, helicopter icing depends on a number of meteorological variables. Attempts to characterize atmospheric icing conditions date well back into the early days of the NACA and are well documented in the literature (ref 1-3). In the late 1940s these data were compiled into a common body of information, subjected to statistical analyses to determine percentile probabilities of icing conditions and formalized into FAR 25 Appendix C (ref 1-4). Subsequently, the UK modified these data and produced a comparable standard. These documents remain the present standards for helicopter ice protection equipment design and qualification for flight in icing conditions.

It will be stated later in this volume that the FAR 25 data may not be entirely appropriate for current helicopter applications. This is due in part to lack of consideration of low altitude icing conditions and also to shortcomings of older airborne meteorological instrumentation. Efforts are currently underway by the United States, FAA, NASA and others to aggregate low altitude data not previously analyzed and to gather additional data to better define the low altitude icing environment. The Working Group agrees that neither FAR 25 or the UK atmospheres are entirely correct, that additional data emphasizing low altitude conditions should be analyzed and/or gathered and that a new atmosphere should be developed for helicopter use.

In addition to the inadequacies of existing atmospheric icing models, a great deal of improvement is possible and recommended regarding forecasting capability. One initiative of the Working Group was to identify certain individuals in the NATO countries who

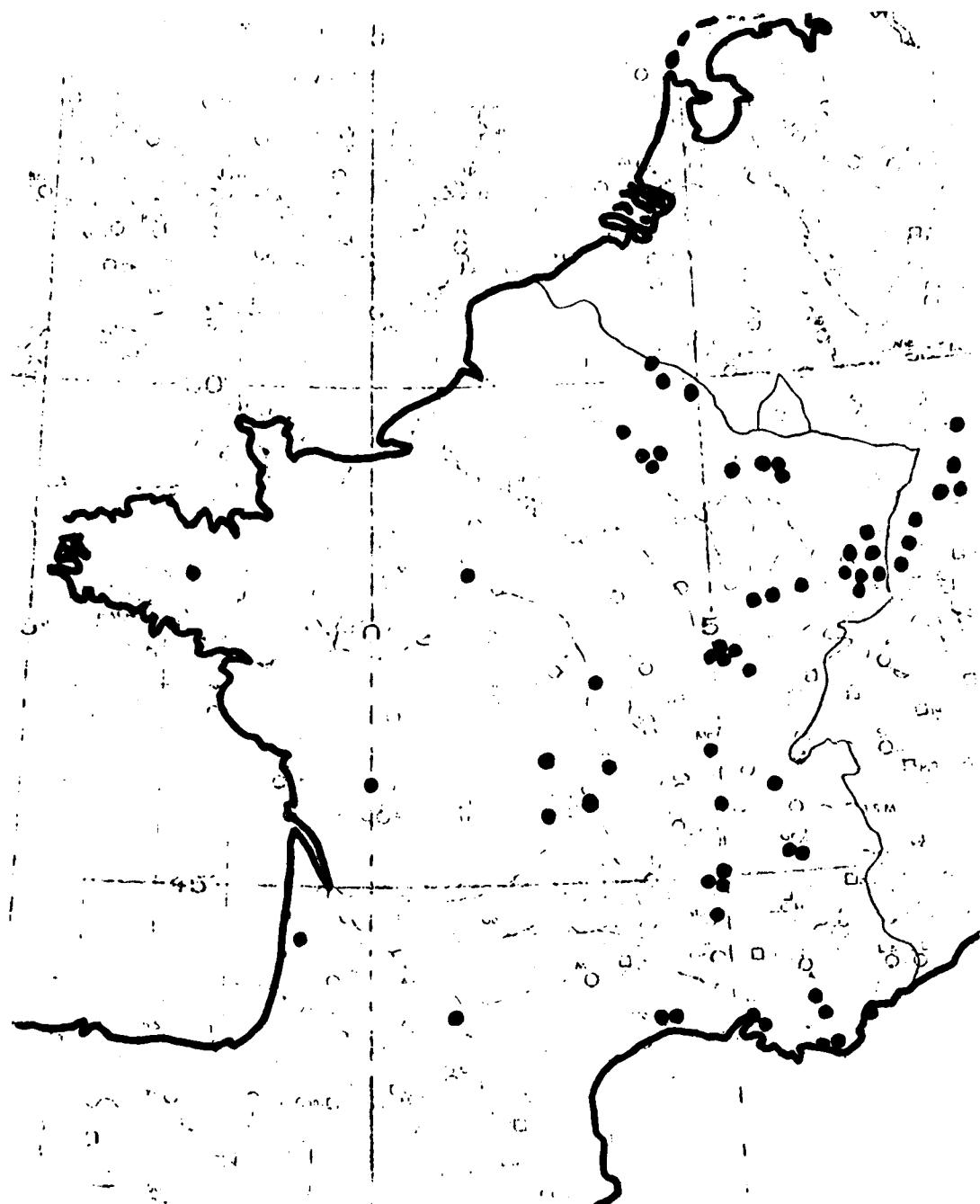


FIGURE 1-7: CASES OF ICING ON PUMA SA 330

13% between SFC and 1000 Ft GND,
6% between 1000 and 5000 Ft GND,
81% above 5000 Ft GND.

are responsible for the measurement of meteorological data. These individuals are listed in Table 1-2. In September 1980, some of the individuals listed in Table 1-2 were contacted to initiate a dialogue about requirements for collection and presentation of meteorological data. Among the items discussed were:

- possible airborne meteorological instrumentation (see Table 1-3)
- an example of the collection of meteorological data in the Federal Republic of Germany
- a description of the presentation of meteorological data in the FRG
- suggestions for data gathering regions

1.4.1 Description of the Collection of Meteorological Data in the Federal Republic of Germany

Test flights are performed if the weather forecaster (Geophysiker) in the aeronautical meteorological station of the Federal Armed Forces Test Center 61 (Erprobungsstelle 61d. BW) forecasts icing areas and icing zones over southern Germany. Of major interest are the upslope areas nearby the Alps (see Figure 1-6). The test flights are performed under the following conditions:

- low stratus in the temperature range from -2°C to -10°C or
- stratocumulus in the temperature range from $+1^{\circ}\text{C}$ to -12°C or
- cumulus congestus with temperatures from -3°C to -12°C in the upper third of the clouds

No flights are carried through in

- freezing rain
- freezing fog and
- cumulonimbus (thunderstorm)

Test flights are conducted until precipitation formation has started. If precipitation forms through ice nuclei (see Figure 1-1), LWC decreases rapidly. Before the icing areas are traversed horizontally, they are traversed vertically by ascending up to the top of clouds or FL 120, so the zone of heaviest icing usually can be determined. An additional test or calibration of the two most important meteorological instruments: --OAT-instrument and hygrometer--is possible, if there is a radiosonde station nearby. (10-868 Munchen, 10-739 Stuttgart, 10-771 Amberg are located within a circle of 150 km around Manching EDSI where the DO 28 is located.)

1.4.2 Description of the presentation of the meteorological data in the FRG

To find a starting point for the presentation of the meteorological data measured in the FRG the graphs of FAR PART 25 are used and data plotted thereon. This will be accomplished in 1981 and provided to the individuals listed in Table 1-2 who will be invited to meet at Manching.

In reference 1-5 some results are reported from 23 flights in icing conditions during 1974 to 1976. They are:

- icing mostly occurred between 4000-8000 ft MSL
- the temperature range was between -4°C to -6°C
- most of the LWC-values were below 0.8 g/m with few up to 1.5 g/m
- the mean effective droplet diameter was very often around 10 to 15 micron

During 4.5 hours or 28 percent of time in icing conditions, the icing intensity was considered to be moderate.

1.4.3 Areas of Major Interest

It can be expected that the number of droplets and the droplet size in a super-cooled cloud will depend on the number of available cloud condensation nuclei (CCN), which in turn depends on whether the cloud is continental or maritime or whether it forms in a polluted or non-polluted atmosphere. So meteorological data should be collected in different areas. It is proposed that these areas include (with the nation responsible for collection in parentheses): upslope areas influenced by the Scottish Highland and the Norwegian Mountains (UK), upslope areas influenced by the Pyrenees and western Alps (France), northern Alps (FRG) (see Figure 1-6). Of similar interest is low stratus over UK, France and Germany.

A second initiative arising from the Working Group is the intention to involve forecasting experts of the NATO countries in the general area of helicopter icing. Some individuals are listed in Table 1-4. An exchange of knowledge and ideas about new icing forecast techniques has not yet started. It will be done as soon as there are more publishable results and experiences from flights in natural icing conditions.

TABLE 1-2
NAMES OF INDIVIDUALS RESPONSIBLE FOR MEASUREMENT OF METEOROLOGICAL DATA

Mr. Martin A. Friedlander Centre d'Essais en Vol France	Dr. E. Hofstee Meteo Amsterdam Airport The Netherlands	Dr. Richard K. Jeck Naval Research Laboratory U.S.A.
Mr. Jean F. Gayet Universite de Clermont II France	Mr. P. Schramm Erprobungsstelle 61 d. Bw Germany	
Dr. P. Ryder Meteorological Office United Kingdom	Mr. K. Uwira BWB-AFB LG III Germany	

TABLE 1-3
GERMAN METEOROLOGICAL INSTRUMENTATION ON THE DO 28

NO	PARAMETER	INSTRUMENT	RECORDING
1	AIRCRAFT ALTITUDE	AIRBORNE SYSTEM	MAGNETIC TAPE
2	AIRSPED	AIRBORNE SYSTEM	MAGNETIC TAPE
3	TEMPERATURE	REC 102 BV	MAGNETIC TAPE
4	LIQUID WATER CONTENT	ICE WARNING DETECTOR NGL (1)	MAGNETIC TAPE
5	VISIBILITY	BACKSCATTER PROBE DFVLR	MAGNETIC TAPE
6	DEW POINT	VAISALA ELEMENT	MAGNETIC TAPE
7	CLOUD EXTENT	SWITCH	MAGNETIC TAPE
8	ICING INTENSITY	ICE WARNING DETECTOR REC 871 FA	MAGNETIC TAPE
9	ICING INTENSITY	ICE WARNING DETECTOR REC IDS 3	MAGNETIC TAPE
10	ICE ACCRETION RATE	ICE WARNING DETECTOR REC IDS 3	MAGNETIC TAPE
11	ICE DETECTOR SIGNAL	ICE WARNING DETECTOR REC IDS 3	MAGNETIC TAPE
12	CLOUD CAMERA RELEASE SIGNAL	MINIATURE CAMERA	MAGNETIC TAPE
13	TIME	TIME CODE GEN.	MAGNETIC TAPE
14	INTERCOMMUNICATION	AIRBORNE SYSTEM	MAGNETIC TAPE
15	EXPOSITION TIME OF OILED SLIDE	OILED SLIDE	MAGNETIC TAPE
16	LIQUID WATER CONTENT OILED SLIDE	OILED SLIDE	MINIATURE FILM
17	DROPLET SIZE	OILED SLIDE	MINIATURE FILM

TABLE 1-4
LIST OF ICING FORECASTING TEAMS

Dr. W. T. Roach Meteorological Office United Kingdom	Mr. P. Schramm Erprobungsstelle 61 d. Bw Germany
Dr. E. Hofstee Meteo Amsterdam Airport The Netherlands	Mr. Petter Dannevig The Norwegian Meteorological Institute Norway

1.5 CONCLUSIONS

Although data do not presently exist which precisely define the occurrence of icing conditions, it can be inferred that approximately 5% of the time on a year-around basis icing will occur at operational helicopter altitudes over central Europe.

Neither the FAR 25 or UK icing atmospheres adequately define the helicopter operational icing environment.

Design criteria for freezing rain, freezing fog, snow and mixed (liquid and crystal) conditions are even less well defined.

Forecasting techniques are currently inadequate to allow unrestricted helicopter operations in icing conditions.

1.6 RECOMMENDATIONS

Additional data emphasizing low altitude conditions should be gathered and analyzed and a new model icing atmosphere should be developed for helicopter use.

Design criteria for freezing rain, freezing fog, snow and mixed (liquid and crystal) conditions require development.

On-going efforts to improve forecasting capability to include greater coordination between cloud physicists, forecasters and helicopter icing specialists should be encouraged.

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Method for Selecting Design Criteria for Icing Protection Equipment
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Manching 1980

2. TECHNOLOGY BASE FOR ICING INSTRUMENTATION AND MATHEMATICAL MODELLING2.1 INSTRUMENT CAPABILITY2.1.1 Instrument Capability for Measurement of Cloud Parameters

The need for a better understanding of the physical, dynamic and thermodynamic aspects of clouds is generally recognized by meteorologists. The Global Atmospheric Research Program (GARP) sponsored by the World Met. Organization (WMO) will be active until the year 2000; several aircraft, ground stations, ships and satellites are involved in this study.

In the narrower field of helicopter icing the cloud parameters which require measurement are, as listed in section 1.1 above, outside air temperature (OAT), the mass concentration of the water substance, its type and size spectrum. Various instruments have been, and are being, developed for this purpose for use in atmospheric research aircraft, in icing trials aircraft and in ground simulation facilities. Their capabilities are discussed below.

Temperature. In icing cloud the static OAT and temperature of the water droplets are relevant parameters. It is assumed that the two temperatures are the same, an assumption which is probably correct when the droplets are very small, but if they are greater than 50 micron diameter they can be warmer or colder than the ambient air due to their movement and thermal inertia. However, for the droplet size range of interest to helicopter icing, the difference in droplet and air temperature can be ignored. The use of radiometric instruments for cloud temperature measurement may be of value in validating this assumption.

Total air temperature is the basic parameter measured in aircraft whilst OAT is the parameter required for icing purposes. All probe-type instruments give indications somewhere between these two values depending on the sensing element. Calibration of the instruments in icing tunnels in dry air and in cloud at various values of liquid water content and airspeed is essential for accurate determination of OAT. Accuracies of $\pm 0.5^\circ\text{C}$ in dry air and $\pm 1.0^\circ\text{C}$ in cloud are considered acceptable for icing purposes, although the latter may be difficult to achieve with existing technology.

There is a number of commercial instruments available, e.g., Rosemount Types 102 and E22001, Normalair Garrett Type 0701 037 011, and research instruments such as the CEV T4113 and A&AEE nickel resistance sensor. Because of sensitivity to pitch and yaw, some are more suited to use on fixed wing research aircraft than on trials helicopters as indicated in Table 2-1.

TABLE 2-1
RECOMMENDED INSTRUMENTS FOR MEASUREMENT OF ICING CONDITIONS

Parameter/Instrument	Atmosph Research	Flight Test	Operational Use
(X: RECOMMENDED O: POSSIBLE)			
Temperature			
Rosemount 102	X	O	?
Rosemount E2201C		X	0
Normalair Garrett	X	O	?
Home made probes	X	X	
Radiometric	X		
LWC			
Leigh		X	X
Rosemount IDS 3	O		
Rosemount 871FF1		X	X
Johnson Williams	X	O	
Ruskin	O		
Accretion Rods			
Teddington hot rod		O	O
A&AEE Vernier		X	O
CEV Temoin		X	O
A&AEE TV-Raster		O	
Particle Size			
Oil Slide	O	O	
Knollenberg 1D	X	O	
Knollenberg 2D	X		
In development			
LWC UMIST - UK	?	?	?
LWC Cambridge Consultants UK		?	?

In simulation facilities it is general practice to derive OAT from measurement of temperature upstream of the water injection system.

Liquid Water Content. Despite its apparent simplicity this fundamental parameter is difficult to measure accurately as evidenced by the variety of instruments which have been developed. Also, care is required in positioning the LWC sensor, especially in helicopters, because the low droplet catch efficiency of the forward fuselage causes enrichment of the LWC in the airflow close to the fuselage.

Currently available instruments have been described fully in various references, e.g., Booker and Barlow (ref 2.1) and their suitability for use on research aircraft and trials helicopters is indicated in Table 2.1.

The basic problem with accretion type instruments, which derive LWC from measurement of ice accretion and cool-down period, is that the dead time of the instrument becomes an increasing portion of the total cycle as LWC and airspeed increases. They are therefore more suited to low speed aircraft, and the latest aspirated models of Leigh and Rosemount 871FF1 have been used successfully in trials helicopters, but their accuracy decreases at high values of LWC and at temperatures approaching 0°C. The Rosemount IDS3 has been used on the German DO28 research aircraft. Visual accretion rods, Teddington hot rod and CEV T6100 Temoin, give an approximation of LWC because they rely on eye-ball measurement of accretion thickness. The A&EE Vernier accretion rod is more accurate, but all accretion rods become less accurate once the Ludlum Limit is exceeded and the accretion shape becomes horned. Visual accretion rods are not recommended for use on research aircraft; they have been used for trials helicopters, but are not ideal.

Thermal type LWC instruments have been used successfully on fixed wing aircraft, but less successfully on helicopters due to pitch and yaw effects. The Johnson Williams instrument has been most widely used but it under-reads if droplets greater than 100 micron diameter are present, and a number of current equipments saturate at LWC greater than 1.0 gm^{-3} at speeds of about 250 knots. However, thermal type equipments have the advantage that they operate as efficiently at temperatures close to 0°C as they do at low temperature.

Of the radiation-type instruments, which have been developed in recent years, the Ruskin type, which is based on the absorption of Lyman-alpha radiation by water vapour, presents many interpretation problems but has value for atmospheric research purposes; it is not suitable for trials helicopters. LWC indications can also be obtained from Knollenberg equipments but their accuracy requires further evaluation. An experimental equipment developed in the UK by University of Manchester Institute of Science & Technology, based on forward scatter of laser radiation, appeared very promising in that it was independent of velocity, droplet size and temperature. However, it was too large for airborne use but development is continuing to reduce the size to an acceptable value for trials helicopters. It is possible that the equipment will also provide a gross indication of droplet VMD.

In simulation facilities, LWC is generally derived from measurement of air mass flow rate and water injection rate. In small icing tunnels the use of a knife-edge probe (ref 2-3,2-4) exposed for a short period has proved of value and has been used to cross-calibrate two facilities in the UK and the NRC Canada icing tunnel.

Water Droplet Sizing. The oil coated slide technique is widely used for determination of droplet size spectrum but errors can result due to impingement effects (droplet shatter and coalescence). Radiation type equipments such as the DFVLR, back scatter technique, Knollenberg FSS100 and ASSP-100, forward scatter, and Knollenberg OAP 200X, shadow technique, are currently coming to the fore and are suitable for research purposes rather than for trials helicopters where their weight, bulk and complexity may prove disadvantageous.

It has been noted by a number of observers, e.g., Keller (ref 2-4), that radiation-type equipments indicate lower values of droplet volume median diameter than obtained with oil slide equipment, a factor which requires consideration in setting up of simulation facilities.

On trials helicopters an approximate indication of droplet size can be obtained from a comparison of LWC indications from instruments with small sensors, e.g., Leigh, and accretion rods of larger diameter, e.g., CEV T6100. The former instrument has a high catch efficiency for small and large droplets whilst the latter has a lower overall catch efficiency so that a major change in LWC indication between the equipments can indicate a gross shift in droplet VMD.

Ice Crystals and Snow. Research studies of atmospheric ice crystals are in progress at a number of places, e.g., the meteorological departments of the Universities of Wyoming and Washington in the USA, the Laboratoire Associe de Meteorologie Physique of the Universite de Clermont in France and the Met. Dept. of the University of Manchester Institute of Science and Technology and the Meteorological Office, Bracknell, in the UK. Typical of the instrumentation used in these research studies are ice particle counters to measure spatial density and Knollenberg 2-D equipment to indicate crystal type. However, there is no instrument currently available for use in trials aircraft for measurement of ice mass concentration nor can the ice-water ratio be determined in mixed conditions.

2.1.2 Instrumentation for Icing Flight Clearance Testing

The instrumentation required for icing flight clearance testing depends on the specific demands of the certifying authority. It can conveniently be considered in 4 classes:

- (a) for measurement of the icing condition parameters as discussed in the previous section
- (b) for measurement of the ice accretion effect on aircraft performance
- (c) for measurement of ice accretion position, shape and size
- (d) for measurement of protection system performance

In the past, assessment of the effects of ice accretion on aircraft performance has varied from subjective assessment by the pilot to highly sophisticated instrumentation installations. The certifying authority should define its requirements in this respect, bearing in mind the type of icing clearance sought (limited or unrestricted) and the operational role of the aircraft.

The group recommends that instrumentation should be fitted to monitor the major engine parameters, including engine air intake depression where this may be critical, to demonstrate that engine performance is not unacceptably degraded by icing of the engine or engine air intake or by ingested ice. Rotor torque, stress and vibration levels should also be recorded, together with the normal parameters associated with handling and performance. It is essential that all these data are recorded with a common time base or other means to allow them to be interrelated. This total instrumentation package should present no problem since all the parameters are normally measured and recorded in clear air flight testing.

A need may exist for an instrument to measure and indicate the excess torque required in the iced condition over that required in clear air. Consideration of such an instrument should be encouraged.

Indication of the position, shape and size of ice accretions on the aircraft can be required to allow decision to be made on safe continuation of the icing flight test, to indicate the performance of the ice protection system, to assist in accountability of any unusual handling or performance incidents and to allow extrapolation of limited test data. In the past this has been achieved by the use of TV cameras and selectable monitors for crucial air intake areas, etc., and rotor head and tail boom cameras have been developed to give photographic coverage of the main rotor upper and lower surfaces. The problem in this area is that of the bulk, weight and flight observer requirement which may limit their use on small aircraft.

Instrumentation to monitor the performance of the ice protection system, other than TV and photographic recording as above, will depend on the type of protection system and the sophistication of the protection system control equipment. It is essential that the crew are provided with indication that any fault in control or operation has occurred and, if this is not included in the basic control system, adequate instrumentation must be installed.

In UK tests the use of rotor blade lag angle potentiometers has given useful information on correlation of individual blade loading with heater mat energisation, and in US and German tests blade surface temperature measurements above the heater mats have been recorded and related to mat sequencing. These latter measurements have been more in the nature of research than of system performance measurement, and are not considered essential to future icing clearance testing.

The need to equip the test aircraft with weather radar is one on which opinion is divided. It is evident that its use can assist in avoidance of hail and precipitation. It may also allow aircraft positioning in the most severe icing condition in cloud. If it is a standard fit on the aircraft its use is recommended but special fitment for icing flight testing is not generally seen as a requirement.

2.1.3 Instrumentation for Operational Use

During flight in icing conditions, information that should be made available to the flight crew depends upon the capabilities of the helicopter. For discussion purposes helicopters can be assumed to fall into one of two categories: unlimited capability and limited capability. If a helicopter has been certified to the full range of icing criteria contained in FAR 25, Appendix C, then it should be capable of operating in 99.9% of the supercooled cloud conditions expected to exist. An aircraft or helicopter having this capability would be fully protected and, so long as the icing conditions being penetrated were supercooled clouds, the flight crew should not be concerned with the icing severity level. Their only information need in this case would be advisory to relate icing encounter and proper ice protection system function. The PUMA (SA-330) is the only helicopter claimed to fall in this category. According to ref 2.5 the PUMA utilizes weather radar to avoid the most severe conditions such as flight in cumulo nimbus clouds. In addition the PUMA is equipped with temperature and ice warning devices to actuate engine air intake and rotor ice protection systems, and to warn the pilot that icing conditions exist.

All other helicopters known to exist within the free world are either restricted from flight in icing conditions or have limited capability for flight in icing conditions with various degrees of protection. Table 2-2 provides a listing of various helicopter types and indications of the type of icing flight restriction or release they may possess along with readily available information pertaining to installed equipment. For the helicopters listed only a very few releases refer to instrumentation as a part of on-board equipment, e.g., S-61 (released by the CAA for operations in light icing conditions), and CH-47D and UH-60A helicopters containing ice protection kits. The S-61 (CAA released) uses an externally mounted small probe to provide ice accretion rate information to the crew and, as well, it is required that the OAT indicator be illuminated since the -5°C temperature limit is considered critical and must be monitored closely.

One conclusion that can be drawn from the data presented in Table 2-2 is that very little attention has been given to operational instrumentation requirements until very recently and the current trend is to provide (for helicopters having limited capability for flight in icing conditions) simple inexpensive accretion rate detection devices and accurate, readable OAT displays. A slightly more sophisticated approach is being implemented on the CH-47D, UH-60A, and the Advanced Attack Helicopter (YAH-64A), i.e., installation of a display of liquid water content from signals produced by an ice detector. The basic philosophy for this display is to warn the flight crew if the icing severity level for which the aircraft are designed to operate (approximately 1.0 gm/m^3) is being exceeded and that evasive action should be taken.

Helicopters that are not capable of prolonged exposure to icing conditions should include devices or instrumentation for day or night use that can warn the flight crew of presence of atmospheric conditions conducive to icing. This of course assumes that the helicopter is certified for day, night, and IMC operations. There have been many discussions at various meetings and symposia on the subject of the need and opinions vary. Little specific research or development has been attempted to define the most suitable approach to the problem. Several schools of thought appear to exist and a summary is attempted as follows:

- (a) Some operational pilots merely want to know if they are in icing conditions and have no desire to quantify the severity of the condition. Their main desire is to know when to activate specific ice protection equipment and/or egress the condition.
- (b) Some operational pilots feel that ice accretion on various external protuberances such as windshield wipers, door hinges, door handles, wing sponsons, etc., is sufficient warning of the icing condition and rate of accretion. This information is sometimes used to form the basis of pilot reports in the form of trace, light or moderate icing conditions.
- (c) Operators of helicopters having specific limited releases that are well-defined desire to know when the limits are being reached so that time is available for evasive action.
- (d) Certifying agencies certainly want the specific limits to be defined and the status provided to the aircrew.
- (e) Air weather service personnel desire pilot reports that can be relayed to other aircraft in the area.
- (f) Some researchers desire that the icing forecasts be improved, feel that forecasts should be related to key parameters indicative of icing severity level, in quantifiable form, such as LWC and OAT. They further desire that all aircraft be equipped with devices that can be used to quantify these parameters for pilot report purposes as well as advising the aircrew of the severity of the condition. They feel that all aircraft limits in terms of OAT and LWC should be defined through test.

The US Army attempted to qualify the UH-1H helicopter during the winter of 1978/79 with a so-called partial ice protection system that included anti-iced windshields and an icing severity level indication system (cockpit display of LWC and accurate OAT) and a modified FM whip antenna installation. Results of limited testing performed indicated that LWC and OAT was not sufficient to define safe operating limits in icing conditions and the idea was not incorporated. The US Army has also performed some experiments with an integrating rate unit developed by Leigh Instruments of Canada Ltd that, in essence, integrates LWC (ice detector signals) as a function of time thereby relieving the pilot from the chore of mentally averaging the LWC variations. Limited testing to date has not yielded good correlation of the IRU display to specific limits of time as a function of LWC or degradation of aircraft performance. It is speculated that the influence of other parameters (other than LWC), e.g., OAT, droplet size, relative humidity, and solar radiation may be influencing the inability to correlate.

US Army test results to date with various helicopters indicate that engine torque rise on some helicopters may be used as an indication that rotor ice accretions are such that autorotation performance may be degraded. Based on limited flight test data the US Army is using a torque rise of approximately 10% to define this limit. One specific problem with this approach is that torque rise (above a preset value) is very difficult to ascertain since engine torque is dependent upon many variables. To emphasize this point, some test results from JUH-1H research testing show that torque rises were not identified in the cockpit by the test pilot during ice accretion; however, significant torque decreases were noted by the pilot (and recorded) during the rotor blade deicing cycle.

TABLE 2-2
ICING FLIGHT CAPABILITY

<u>AIRCRAFT</u>	<u>USER</u>	<u> IMPLIED RELEASE*</u>	<u>INSTALLED EQUIPMENT</u>
PUMA	France	Unlimited	full protection
UH-1F	USAF	TRACE	pitot, windshield defogger, engine anti-ice
AH-1G	USA	Light	engine anti-ice, pitot
AH-1J	USN	Icing Conditions	windshield, pitot, engine anti-ice
UH-1H	USA	Light	Pitot, engine, windshield defogger remove barrier screens
UH-1N	USN	-5°C TRACE	not defined
UH-1F/1L TH-1L/HH-1K	USAF	Icing Conditions	not defined
UH-2A/B	USN	Not Recommended	rotor deice, engine & windshield anti-ice, pitot
SH-2DF		Restricted	windshield, pitot, turbine
SH-3A/G HH-3A	USAF	Restricted (Avoid)	windshield, engine inlet, inlet deflectors
CH-3E/HH-3F	USAF	TRACE Light	engine inlet, pitot rotor blade polyethelene tape
HH-3P/F	USAF	+5°C Icing Conditions	without inlet deflector with inlet deflector
OH-6A	Army	+5°C or below	engine anti-ice
CH-21B/HH-21B	Army USAF	prohibited	pitot carb, windshield defrost
H-46A/D/F	Navy	prohibited	unknown
CH-46E	Navy	prohibited	blade, engine, engine inlet, pitot
CH-47A/B/C	Army	Light (precautions)	engine, pitot, yaw port, windshield anti-icing engine FOD screen
CH-53A/D	USAF	Avoid	not defined
HH-53B/C CH-53C	USAF	permissible but avoid	EAPS doors
CH-53E	USAF	Light (30 min)	engine, windshield, pitot, engine inlet
CH-54A	Army	No limits Limits defined	special engine Bellmouth without special Bellmouth
CH-54B	Army	Avoid	not defined
BO-105	FRG	Prohibited	not defined
S-61N	US	Not Released	not defined
S-61N	UK	Light (-5°C) In a limited geographical area	NOTE: Other provisions of release Max Altitude = 5000' Freezing level 500' T.O. Weight = Max -1000# Torque Limit of 3 to 4% rize Airspeed = 20 kt Engine inlet deflectors, ice detector rod (illuminated for night flying) HF antenna restraint, Illuminated OAT gage windshield anti-icing + pitot, engine anti-ice
CH-47D	Army	Light	engines, FOD screen, windshield, pitot, LWC display (NOTE: heated rotor blades were developed but not fielded)
UH-60A	Army	Moderate	rotor system, engine, engine inlet, windshield, pitot, LWC display

*Interpretation of statements in Flight Manual

The UK has been experimenting with a means of displaying 'pure' torque, i.e., the increment of engine torque rise directly attributable to ice formations on the helicopter. This technique could be beneficial and a useful method of ascertaining the effect ice is having upon the aircraft and would provide a ready basis for determining if and when operational limits were being approached. This technique entails measurement and computer processing of many parameters and has not yet shown good correlation.

Based on test results to date and experimentation with various helicopters and types of instrumentation, although opinions vary significantly, the following instrumentation should be used on aircraft intended for flight in icing conditions:

Aircraft with limited release: Liquid Water Content - This parameter is considered most indicative of the icing severity and can be used for several purposes, e.g., to quantify the severity of the icing condition for comparison with quantified limits that should have been established through flight tests. Use of such terminology as trace, light, moderate icing conditions is subjective, totally misunderstood and misleading.

Outside Air Temperature - This parameter is normally measured and displayed to the flight crew. The display should be readable and the sensing device should be of sufficient accuracy to provide to the pilot an accurate (-0.5°C) measurement of static ambient temperature for day and night use. This is considered necessary since very slight temperature changes can influence rotor ice shapes that directly impact rotor performance degradations. Test results to date indicate that specific ranges of static temperature are critical while temperature ranges above and below that range are not as critical.

Integrated Total Damage - Technology for instrumentation of this type is not yet available; however, testing to date indicates that an integration of LWC and OAT as a function of time may be correlatable to total ice accretion on the rotor blade as well as critical ice shapes most damaging to rotor performance.

'Pure' Torque - Again technology is not yet available; however, display of 'pure' torque (increment of torque rise attributable to ice formation) would provide the most accurate indication of 'total damage'. 'Pure' torque indications could be used to forewarn aircrews of impending limits and/or activation of rotor deicing systems.

2.1.4 Recommended R&D

In the case of trials aircraft, and for the acquisition of meteorological data, there is a need to develop improved capability for LWC measurement at temperatures close to 0°C, at LWC greater than 1.0 gm⁻³, for the measurement of ice crystal and snow mass concentration and the ice-water ratio in mixed conditions. There is also a need for a low bulk equipment for droplet size measurement. For trials aircraft there is a need for improved techniques for photography of ice accretion and shedding from the main rotor blades to allow comparison of flight, simulator and analytical model results and to provide information on accretion shape for aerodynamic studies.

The instrumentation required for operational aircraft has not yet been clearly established. Nevertheless, it is recommended that consideration be given to the development of equipment to indicate the torque increase due to ice accretion, to quantify the severity of the icing condition (with LWC, VMD and temperature inputs) and for the remote sensing of icing condition severity.

2.2 MATHEMATICAL MODELLING OF ROTORCRAFT ICING

2.2.1 General

The increased interest in the rotorcraft icing problem has coincided with the desire for all weather helicopters for both civilian and military applications. The desire to address the helicopter icing problem with an analytical approach is due mainly to the recent rapid rise in computing capability available, as the basic equations governing droplet trajectories, ice accretion, and conduction heat transfer have been known for many years.

The helicopter presents a particularly difficult challenge to an icing analysis since the interactions between the various components (e.g., rotors and fuselage, rotors and inlets, and fuselage and inlets) can make the aerodynamic flow field computations extremely difficult. In fact a complete calculation of the aerodynamic environment which includes all the interactions is beyond the current state of the art. Thus any icing analysis must be predicated on making certain initial simplifying assumptions as to how the helicopter of interest will be treated. These assumptions must be made in order to simplify the analysis to manageable proportions while at the same time retaining the essential features of the aerodynamic flowfield. These two requirements are often conflicting.

The assumptions made would be dependent on the component of interest. With regard to the main rotor, decisions must be made as to how many blades to treat (i.e., an isolated blade or multiple blades with interactions) and how to model the wake(s) of the blade(s). Also attention must be paid to the question of whether to treat the hover or forward flight case. The hover condition is somewhat 'easier' to treat in that a rotational symmetry is present which is not present for the forward flight case.

The calculation of rotor flow fields is a complete subject unto itself and remains an active research area. Because of the inherent complexities of performing such analyses, past (as well as current) icing analysis efforts have been generally confined to treating

isolated, two dimensional blade elements operating in the hover mode. These two dimensional calculations are combined using a strip theory approach to predict the isolated rotor performance in the icing environment. While such an analysis approach has some possibly severe limitations, the results can nevertheless increase the understanding of the actual rotor icing problem.

The following sections will treat individually each of the appropriate portions of the total rotor icing analysis:

2.2.2. Droplet Impingement Analysis

The basic governing equations for the trajectories of particles in flowfields are well documented in the literature (e.g., ref 2.6). Main interest is generally in the calculation of spherical water droplet trajectories but more recently interest has been in the calculation of trajectories for ice crystals and snow flakes (refs 2.7, 2.8). The equations of motion for the particles are based on the assumption that bulk fluid flow is not affected by the particles and the particles move under the influence of the drag force. The analysis has been extended to include the effects of gravity and buoyancy (ref 2.7) but these effects are of second order importance for most cases of interest.

An important input parameter into the equations of motion is the value of the drag coefficient. For spherical water droplets, a large data base of drag coefficient level is available, while the data base for snowflakes and ice crystals is much less complete and thus the accuracy of the trajectory calculations for these particles must be questioned.

Another area of interest is that of shed ice trajectories in the immediate vicinity of aircraft and rotorcraft. Data on representative shed ice shapes and resultant force coefficients are almost non-existent.

To calculate particle trajectories, a computation must first be made of the aerodynamic flowfield. Rotor blades in hover are currently analysed by first considering a series of two-dimensional airfoil analyses and then combining the results using a strip analysis approach. The flowfield for each airfoil section is computed by either some incompressible flow technique (surface singularity or Laplace equation solution) possibly followed by a compressibility correction or by a direct compressible flowfield calculation.

The final accuracy of the particle trajectory calculations is strongly dependent on the accurate determination of the airfoil flowfield velocity vectors at the positions of interest. If a grid scheme is used to pass the airfoil flowfield to the particle trajectory program care must be taken in choosing not only the grid work of positions but also the interpolation scheme to be used. The grid must be sufficiently fine in the area of rapid flowfield accelerations.

The particle trajectory computations yield fundamental information on the efficiency of an airfoil to catch particles of various sizes and configurations for various flight conditions and thus give the first indication of that body's susceptibility to icing.

Typical output of such trajectory calculations is shown in Figures 2-1 and 2-2 for an NACA 0012 airfoil with a chord of .415 m, a free-stream Mach number of 0.4 and an angle-of-attack of 8 degrees. Figure 2-1 shows the 20 micron droplet trajectories about the airfoil while Figure 2-2 shows the corresponding variation of local collection efficiency for the 20 and 40 micron diameter water droplets.

The differences between the 20 and 40 micron diameter droplet trajectories are reflected in the local collection efficiency curves shown in Figure 2-2. The levels of the collection efficiency are proportional to the local water catch rate of the body for the particular size of droplets. The local collection efficiency is a ratio of the actual water impingement rate on a differential area to the maximum possible water impingement rate on that surface.

2.2.3 Ice Accretion Analysis

The basic energy balance which occurs at the surface of an unheated body in an icing encounter were first presented by Hardy (ref 2.8) and Tribus (ref 2.9) and then generalized by Messinger (ref 2.10) whose interest was in predicting surface temperatures for deicing applications.

Werner (ref 2.11) further extended Messinger's analysis to include the effects of runback water and body axial conduction. Werner used the analysis to predict the patterns of ice growth rate for a rotor blade operating in a sea level hover condition. He compared the predictions with some limited experimental data for rotor blade ice accretions and concluded that a qualitative agreement existed. However no detailed comparisons were made to attempt to validate the model.

Lozowski et al (ref 2.12) recognized the lack of adequate detailed ice accretion experimental data required for model verification so they chose to consider the simplified case of cylinder icing for which ample impingement information is readily available. They used the basic analysis technique set forth by Messinger and Werner to predict the ice accretions on a cylinder for a matrix of conditions (liquid water content, air velocity, and air temperature). They supported this analysis with a comprehensive experimental test program to measure the detailed ice shape characteristics on the cylinder in order to assess the accuracy of the model.

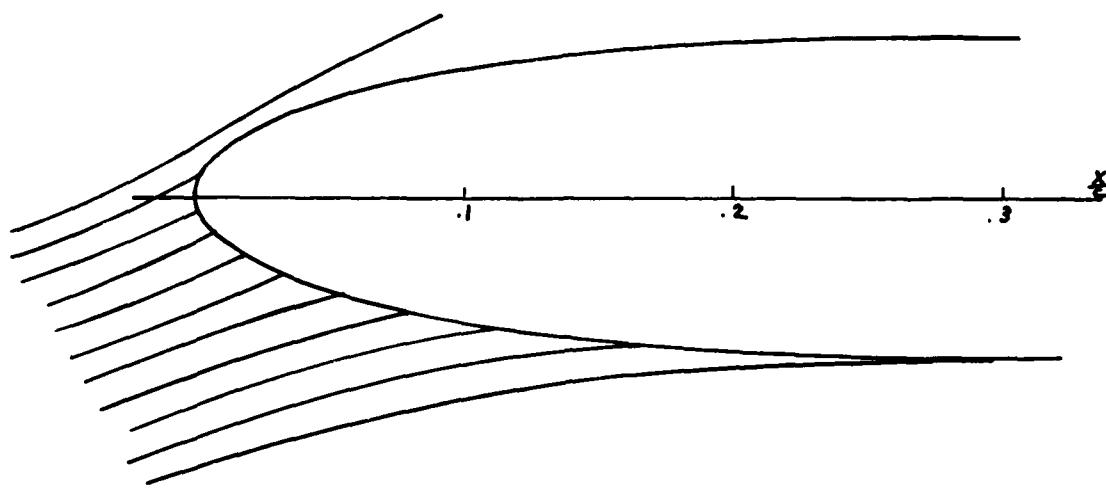


FIGURE 2-1 $20 \mu\text{m}$ DIAMETER WATER DROPLET TRAJECTORIES FOR NACA 0012 AIRFOIL WITH 0.415 m CHORD, $M_\infty=0.4, \alpha=8^\circ$

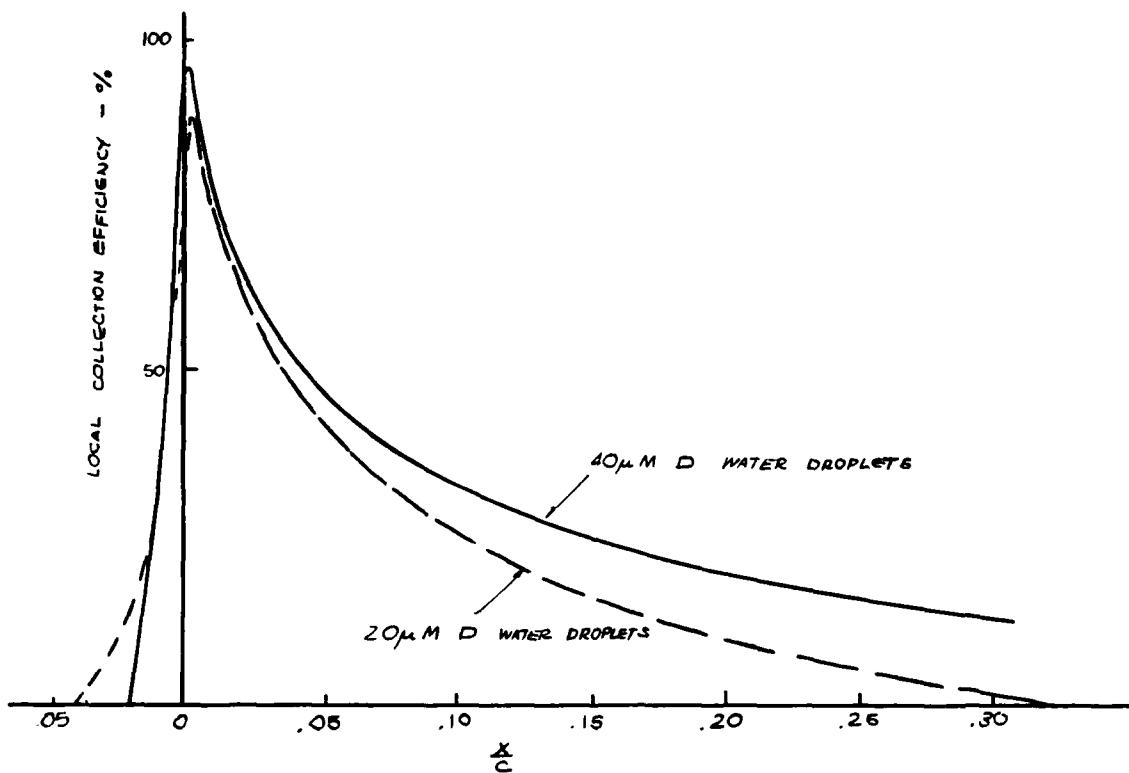


FIGURE 2-2 LOCAL COLLECTION EFFICIENCY VARIATION FOR NACA 0012 AIRFOIL WITH 0.415 m CHORD, $M_\infty=0.4, \alpha=8^\circ$

Figure 2-3 presents two typical comparisons taken from ref 2-12 -- one for rime ice growth and the other for glaze ice growth. As the figure indicates, the agreement with the experimental ice shape profile is much better for the rime ice case. Figure 2-4 presents the predicted cylinder surface temperature profiles for two comparable cases to those shown in Figure 2-3 with the corresponding experimental measurements made in a later experimental program. Again the agreement is much better for the rime ice case. Lozowski, et al, attribute the discrepancies between model predictions and experimental results as possibly being due to any of a number of factors. Of particular concern is the fact that the accretion model calculates an initial icing rate distribution around the clean cylinder by solving the heat balance at specified angular locations and then it is assumed that the growth rate distribution does not change with time so as to give the final ice shape. Thus the model does not account for time-dependent changes in such key variables as local collection efficiency and local surface convective heat transfer coefficient. As the ice builds up on the cylinder surface the shape of the body can change rather significantly and the effects of such a large-scale geometry change are not presently accounted for in the determination of local collection efficiency.

Studies done to date indicate that the local heat transfer coefficient has a large effect on the resulting ice shape and surface temperature distribution. Figure 2-4 shows the difference in predicted ice shapes, using the Lozowski/Stallabrass model, which can arise depending only on whether a rough or smooth cylinder heat transfer coefficient distribution is assumed. Figure 2-5 shows the significant difference in predicted surface temperature distribution depending again only on the selection of rough or smooth cylinder heat transfer coefficient distribution. An adequate understanding of the levels of convective heat transfer from such arbitrarily shaped bodies with large scale nonordered surface roughness and impacting, freezing, and possibly runback water droplets is clearly lacking.

Ackley and Templeton (ref 2.14) attempted to account for the time dependent effects on collection efficiency and convective heat transfer coefficient distribution in their analysis of the icing of a cylinder. However, they constrained the geometry of the ice growth cross section to be that of an ellipse to simplify the trajectory calculations. As such the analysis can only hope to agree with experiment for these conditions which result in the rime icing of a cylinder. That is, the model cannot predict any of the classical double horn ice growth characteristic of glaze icing.

Currently efforts are underway by NASA, RAE, and Lozowski at the University of Alberta, Canada to generalize the ice accretion model to airfoils and intakes of various geometries and incorporate time dependency into such calculations. Efforts are also underway by NASA to acquire the required experimental ice accretion data to verify the accretion model. Attempts are also being made by NASA to measure local convective heat transfer coefficients for simulated ice shapes to compare with the predicted levels of heat transfer using available techniques.

Individual terms of the standard heat balance are also being investigated by the RAE to improve the formulation and to determine the need for additional supporting experiments to be conducted. NASA is sponsoring research to gain a better understanding of the detailed physics of droplet impact, freezing, and runback through fundamental analytical and experimental studies. In addition, the importance of modeling water runback kinematics, droplet splashing, and runback water shedding will require further investigation.

Lozowski et al (ref 2.12) also generalized the heat balance to include the case of mixed icing (supercooled water droplets and ice crystals). However, the experiments they conducted revealed that their hypotheses on the features of ice crystal deposition on the cylinder surface were in error. Clearly, a better understanding of the mixed icing condition is also required.

2.2.4 Thermal Anti-/Deicing Analysis

Currently, one-dimensional, transient finite difference analyses are performed to predict the temperature profiles through a multi-layer rotor blade structure with a specified ice deposit during a thermal deicing cycle. Generally, the aim is to determine, for a given configuration and electro-thermal power level, the heating time required to bring the ice-blade element surface interfacial temperature to 0°C. Such a thermal analysis along with an ice accretion analysis to predict the ice thickness can be used to aid in the design of a rotor electro-thermal deicing system, including the spatial distribution of power input.

However, the one-dimensional analysis yields optimistic results for predicting required 'energy on' time relative to the required times determined by natural or artificial icing tests. Stallabrass (ref 2-15) attributed these discrepancies as being due to three main effects: (1) the presence of two and three-dimensional heat flow in contrast to the idealized one-dimensional treatment of the mode, (2) the effect of the delayed heating of the gaps between adjacent heater elements, and (3) the effects of the moving ice-water interface. Stallabrass used a two-dimensional, transient finite difference analysis for a rectangular geometry to attempt to determine the effects of these various influences and found that the net effect of those influences could increase the required energy-on times by a factor of four.

Currently efforts are underway by the RAE to extend the one-dimensional, transient analysis to include a description of the shedding of the ice from the rotor surface at some prescribed-time after interfacial temperature reaches 0°C and continued heating of

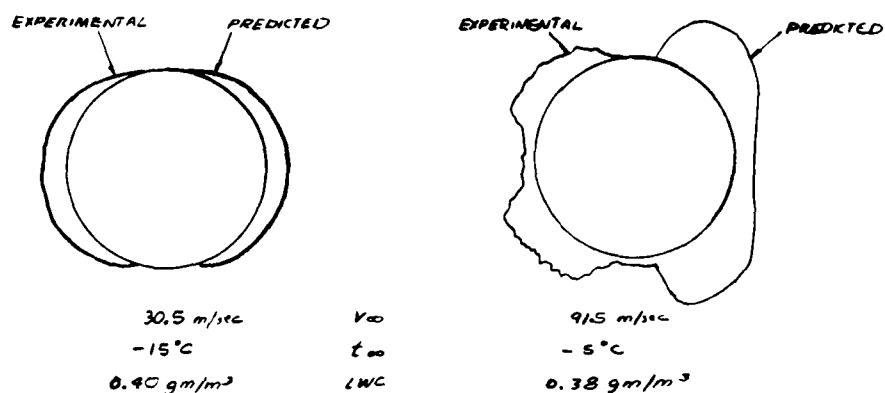


FIGURE 2-3 PREDICTED AND EXPERIMENTAL CYLINDER ICING SHAPES USING LOZOWSKI/STALLABRASS TECHNIQUE (REF 2-12)

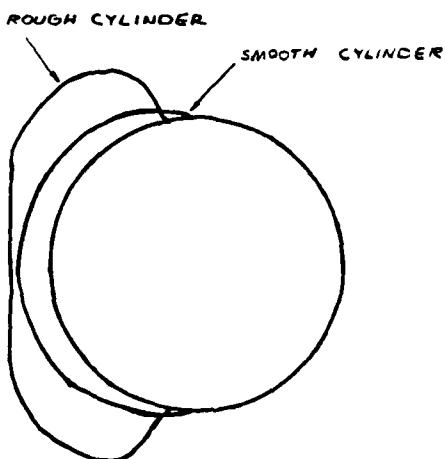


FIGURE 2-4 EFFECT OF HEAT TRANSFER COEFFICIENT SPECIFICATION ON PREDICTED CYLINDER ICING SHAPE USING LOZOWSKI/STALLABRASS TECHNIQUE (REF 2-12)

$$V_\infty = 120 \text{ m/sec} \quad \text{LWC} = 1.25 \text{ gm/m}^3, \quad t_\infty = -15^\circ\text{C}$$

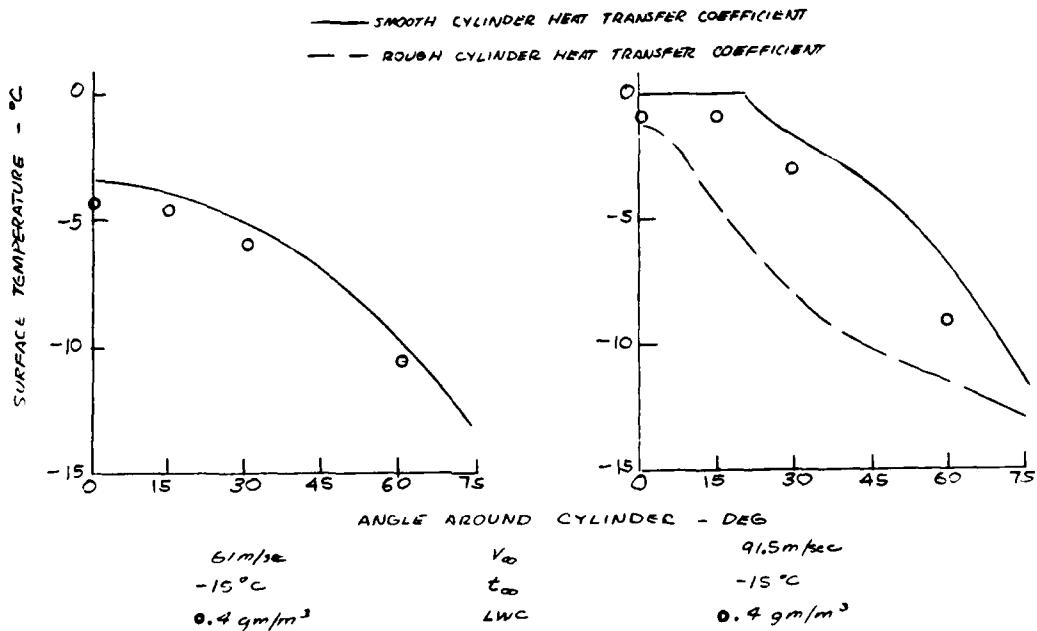


FIGURE 2-5 PREDICTED AND EXPERIMENTAL CYLINDER SURFACE TEMPERATURES USING LOZOWSKI/STALLABRASS TECHNIQUE (REF 13)

the rotor element for the remainder of the prescribed energy-on time followed by a cooling down during the prescribed energy-off time; included in the analysis will be an actual icing energy balance occurring at the ice-air or blade-air interface (as appropriate) and its effect on the element temperature distribution.

Two-dimensional, transient analysis is being developed by NASA and RAE to treat actual rotor geometries rather than the idealized rectangular geometries which are currently used in the analysis.

2.2.5 Aerodynamic Performance Degradation and its Effects

2.2.5.1 Rotor Ice - General

The presence of rotor ice leads to degradation of the aerodynamic effectiveness of the blades, the extent depending on the chordwise and spanwise shape of the accretion. Generally speaking, degradation due to streamline (rime) ice on the nose or runback (glaze) ice more downstream is relatively small. Mushroom ice on the nose is however very unfavourable; profile drag may rise several hundred percent and stall angle may decrease considerably. The position of the ice horns in the flowfield is very important in this connection. On a blade section, an ice deposit on the suction side will disturb the flowfield far more than a similar deposit on the pressure side. Depending on the position of the horns, mushroom ice of relatively small size can cause sizeable degradation of sectional profile drag and stall characteristics.

The ice growth along the rotor increases in the spanwise direction (toward the tip) as the ambient temperature decreases and/or as the liquid water content increases. The ice shape, however, is not easily defined because of the leading edge surface temperature distribution (resultant of ambient temperature, water impingement rate, freezing rate, and aerodynamic heating), aerodynamic and centrifugal forces which are interacting as the rotor passes through the icing cloud. The non-uniformity of these parameters combined with the varying blade angle of attack in forward flight makes analysis difficult.

The sectional characteristics having the largest impact on rotor limits are:

- (a) The maximum lift coefficient at Mach numbers from 0.3 to 0.5 (retreating blade)
- (b) The drag divergence and pitching moment characteristics at the advancing blade tip
- (c) The overall sectional pitching moment
- (d) The change in overall profile drag

The effect of rotor ice on rotorcraft performance, handling qualities and flight safety is determined by the combination (or interaction) of the following factors:

- (a) The rotor airfoil geometry (i.e., chord, thickness, external contour, bending, twist)
- (b) The rotor diameter, rpm & number of blades
- (c) The rotor system type (i.e., rigid, teetering, articulated, etc.)
- (d) The environmental conditions in which the rotor is immersed (i.e., icing intensity, ambient temperature)
- (e) Blade spanwise loading (function of rotorcraft gross weight, rotor disc area, solidity and airfoil geometry)
- (f) The blade thermodynamic properties (i.e., thermal capacity of blade material, surface thermal conductivity)
- (g) Blade surface mechanical properties (i.e., retention capability (local shear and bending stress))
- (h) The use (or non-use) of a rotor deicing system (passive or active)

Helicopter icing tests (Hover Spray Rig, HISS, Natural) have indicated that the rotor ice effect on a helicopter is very configuration dependent (i.e., rotor geometry, blade loading, rotor leading edge surface properties). The specific configuration influences, however, have not been determined, although it is estimated that various types of new technology sections, e.g. low drag aerofoils, on which an aerodynamically refined nose shape is employed, will be very sensitive to ice accretion.

Depending upon the spanwise and chordwise shape and extent, rotor ice may cause: increase of power required, increase in vibration levels and control loads and decrease of autorotational capability.

2.2.5.2 Performance in Horizontal Flight

The performance and blade load characteristics of a helicopter rotor in horizontal flight are dominated by the outboard 40 percent of the advancing and retreating blades. A rise of sectional profile drag and the occurrence of ice-induced premature blade stall on this part are very detrimental in increasing power required.

No general rule can be given for the acceptable extent of performance loss as this depends on the power reserve of the particular helicopter involved. In this respect most modern helicopters are in a more favourable position than those of older generations.

However, the vulnerability of a helicopter to ice-induced performance losses can be reduced by selecting flight conditions such that more excess power is available. Therefore, if this is required, flight in icing conditions should be performed at reduced weight, cruising speed and altitude which will decrease mean blade incidence giving a larger margin to blade stall.

2.2.5.3 Autorotational Performance

To fly a helicopter safely requires, amongst other things, that its autorotation performance is acceptable. A proper autorotational capability is especially important when flying in icing conditions because that situation involves a higher risk of engine failure due to ice ingestion in the intake.

During steady autorotative descent, the aerodynamic forces which drive the rotor are generated in the inner, so-called "accelerating" part of the rotordisc. If the profile drag at a blade section increases, the vector which represents the total aerodynamic force tilts backwards, which has a "decelerating" effect. Then, to compensate for this, the rate of descent must be increased. If this cannot be realised by decreasing directly the rotor thrust, because the collective control level had already reached its full-down position, the rotor rpm will decrease first, resulting in a decrease of rotor thrust.

A new steady state will be reached at lower rpm, larger rate of descent and a larger mean blade angle of attack. If the rotor blades stall along a too extended part, the rotor will cease to autorotate.

The inner part of the rotor operates in a range of large angles of attack at which ice-induced premature blade stall could occur easily. This may explain several experiences reported in the literature of serious degradation of autorotation performance due to only very modest ice deposits on the blades. Apparently in such situations ice had been accreted in an aerodynamically vital area on the suction side of the blade.

During the landing phase after an autorotative descent, collective pitch is increased by the pilot to reduce the vertical speed. The aerodynamic conditions of the rotor are then very similar to those in powered flight. However, while due to ice accretion on the blades the rate of descent may be larger, the maximum thrust capability of the rotor may be reduced owing to premature blade stall. Moreover, it may have been difficult to speed up the rotor during the flare prior to the landing phase onto the maximum allowable rpm. This means that the helicopter has a degraded maximum thrust and rotational energy capability, which deficiencies may be fatal during the landing.

2.2.5.4 Evaluation of the Effect of Ice Accumulation

The analytical assessment of the effect of ice accumulation on rotor performance and loads could be carried out by following the procedure outlined below. The procedure would utilize methods which are generally available at this time, e.g., ref 2.15, although in some areas further theoretical development and some experimental evidence are necessary.

The assessment of the effect of ice accumulation on rotor blades includes the following steps:

- (1) Definition of ice shapes and accumulation features on rotor blades over a given range of flight and weather conditions.
- (2) Evaluation of the effect of ice accumulation on the sectional aerodynamic and dynamic characteristics of rotor blades.
- (3) Determination of performance penalties
- (4) Assessment of blade and control load penalties due to:
 - Uniform and steady ice buildup
 - Uneven buildup and/or natural shedding
- (5) Evaluation of problems related to the deployment of deicing systems
- (6) Assessment of the effect of residual ice accumulation in the presence of active deicing (e.g., runback ice).

The most difficult task appears to be the determination of accurate ice shapes occurring over rotor blades in flight. For, in order to make more detailed predictions of rotor performance and control loads, the rotor aerodynamic analysis program employed must have detailed information on the aerodynamic characteristics of the degraded airfoil. In particular the lift, drag and moment coefficients as a function of ice shape must be known. Since the number of potential ice shapes is literally infinite, general correlations of lift, drag, and moment coefficients as a function of appropriate icing parameter(s) must be found. Currently, these relationships do not exist. If ice accumulation could be monitored with some degree of accuracy, experimental and theoretical interjections could be then directed to quantify the aerodynamic and dynamic consequences of rotor blade icing, and a rigorous approach to deicing systems and flight safety could be then defined.

An alternate approach to determine the section aerodynamic characteristics by empirical correlation of lift, drag, and moment coefficient data gathered in icing wind tunnel tests is to use available airfoil aerodynamic analysis techniques in conjunction

with an ice accretion modelling technique to predict the lift, drag, and moment coefficients for given predicted ice shapes. This approach removes the need for any performance correlations. An initial attempt to predict the performance of an airfoil with an experimentally measured ice accretion was presented in ref 2.17. For the one comparison case presented, the analysis underpredicted the measured drag coefficient by .004 ($C_{dexp} = .014$, $C_{dcalc} = .010$). The authors attributed these discrepancies as being due to the inability of the analysis to handle the large-scale roughness present at the surface of the accreted ice as well as any boundary layer separation and/or reattachment present.

Currently efforts are underway by NASA to investigate more thoroughly the capability of current airfoil analysis codes to accurately predict airfoil performance with accreted ice. Windtunnel tests are also being planned by NASA and RAE to measure airfoil aerodynamic characteristics as a function of accreted ice shape.

The analytical/experimental process to quantify rotor blade icing is summarised in Table 2-3.

TABLE 2-3 ROTOR ICING EVALUATION REQUIREMENTS		
TASK	CURRENTLY AVAILABLE METHODS	RESEARCH REQUIREMENTS
Definition of Ice Shapes and Accumulation Patterns	<ul style="list-style-type: none"> - Fixed wing tests - Fixed incidence 2-D impingement and accumulation calculation 	<ul style="list-style-type: none"> - Oscillatory tests for ice accumulation at constant Mach number over a range of mean angles of attack and pitch oscillation amplitudes - Validation of averaged ice accumulation shapes from fixed incidence calculations at constant Mach number - Extension of ice shape averaging to variable incidence and Mach number - Empirical determination of surface roughness conditions
Evaluation of the degradation in sectional characteristics due to ice accretion	<ul style="list-style-type: none"> - Subcritical potential flow/boundary layer interaction methods - Viscous transonic flow analysis - Preliminary 2-D separated flow analysis - Two-dimensional wind tunnel tests with simulated ice shapes 	<ul style="list-style-type: none"> - Modification of separated flow analysis methods to handle specifically ice accumulation problems - Improved methods to assess the impact of surface (ice) roughness - Thick boundary layer methods
Preparation of sets of airfoil data reflecting the effect of ice accumulation	<ul style="list-style-type: none"> - At present airfoil tables of lift, drag and pitching moment characteristics are prepared by hand and input in rotor analysis computer program over a very limited number of spanwise stations (3 to 5 maximum) 	<ul style="list-style-type: none"> - The preparation of airfoil tables would have to be automated to whatever degree is possible if a large number of ice shape variations is to be considered - Rotor performance and loads analysis computer programs will have to be altered to accept an airfoil table for each computation bay (up to 16 computation stations)
Evaluation of the effect of ice on local blade properties	<ul style="list-style-type: none"> - Changes in mass distribution due to ice accumulation can be easily evaluated 	<ul style="list-style-type: none"> - Changes in elastic properties (torsional and flapwise stiffness) as a function of ice will have to be determined - Blade analysis programs will have to be able to account properly for the extension of ice beyond the leading edge. The reference axis for the definition of pitching moment coefficients will have to be standardized
Assessment of rotor performance penalties	<ul style="list-style-type: none"> - Current rotor performance analysis computer programs are available by means of which rotor performance degradation due to degradation in sectional characteristics can be evaluated - Flight tests provide selected performance and loads data but little information on ice shapes - Model rotor tests can be run with assumed ice shapes 	<ul style="list-style-type: none"> - Model/full scale tests with realistic ice shapes - Flight tests with complete performance and loads instrumentation, and advanced ice monitoring techniques
Evaluation of loads penalties	<ul style="list-style-type: none"> - Performance and loads analysis should not be separated; however computer programs are available in which the dynamics of the rotor is defined in more detail than the aerodynamics. Current dynamics programs are not equipped to handle specifically ice problems 	<ul style="list-style-type: none"> - Modify loads (dynamics) analysis codes to allow the investigation of both steady ice accumulation and uneven shedding

2.3 EXPERIMENTAL VERIFICATION OF MATHEMATICAL MODELS

2.3.1 Tests of Non-Rotating Specimens

Due to the lack of adequate test facilities and to the difficulties and expense of flight trials, the use of proven mathematical models in the design of protection systems is very desirable. Verification of the models described in Section 2.2 is essential and experiments to this end are included in various national programmes. The results of some of these studies are summarised below:

a. Surface Temperature in Dry Air

In the UK, Cansdale (ref 2.18) has confirmed the theoretical relationship between surface temperature, pressure distribution and Mach number in dry air. In his studies 150 mm chord, 290 mm span wooden aerofoils, each having a chordwise array of ten 50 μm thermocouples inset in its surface, were tested in the 300 mm square working section at Artington. Tests covered a range of incidence values up to stall, at Mach numbers of 0.2, 0.3 and 0.4 (the tunnel limit) with a few tests in oscillated pitch. Tests to date have been on NACA 0012 and NPL 9615 (Lynx) sections. A further specimen is being made to an advanced cambered section.

Figure 2-6 shows the typical relationship between measured and predicted surface temperature.

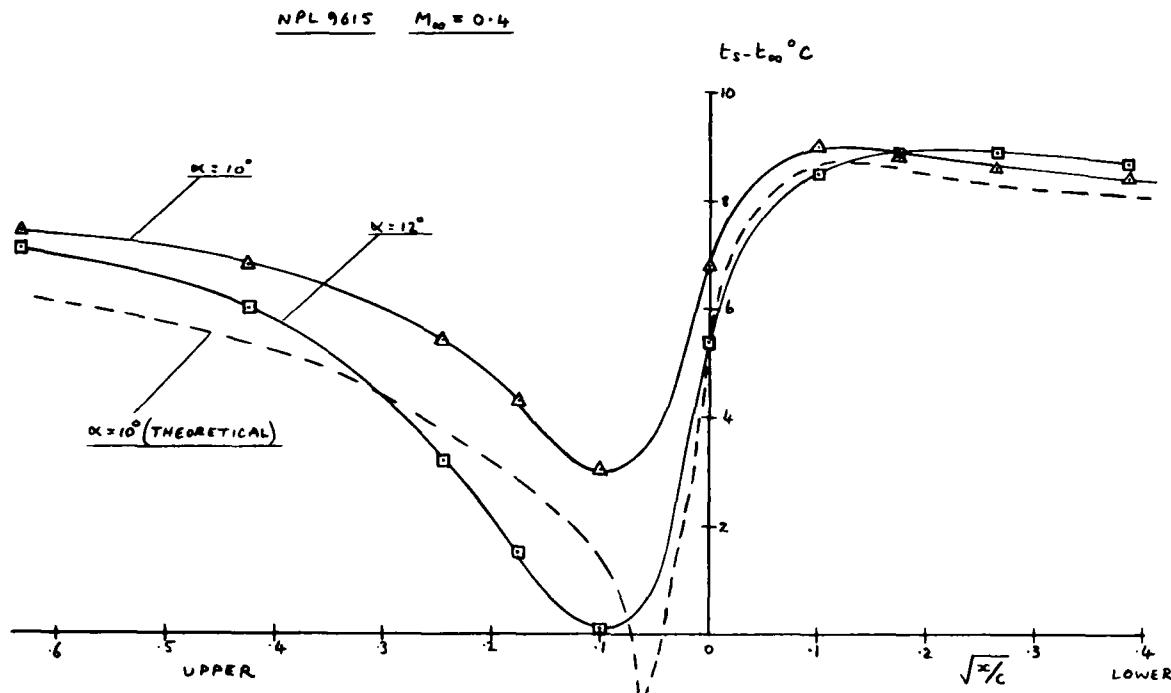


FIGURE 2-6 CHORDWISE TEMPERATURE DISTRIBUTION IN DRY AIR
(NPL9615, MACH NO = 0.4)

In similar temperature survey tests made by Cansdale on sections of Lynx, Puma and Wessex main rotor blades in the 762 mm open jet blowing nozzle at Cell 3W, NGTE, lower than predicted temperature variations round the chord in dry air were obtained: this discrepancy is attributed to the low aspect ratio of the specimens resulting in unrepresentative pressure distribution on the full scale blades.

In the UK, a Puma blade has been fitted with a chordwise thermocouple array at 3 spanwise positions to measure blade surface temperature in hover at fixed incidence and also to measure the effect of cyclic pitch and velocity variation in forward flight in clear air.

b. Surface Temperature in Cloud

In his studies with the 150 mm chord specimens Cansdale verified the prediction of local temperature drop due to evaporative cooling from the wet surface in cloud at above-zero temperature.

In his tests of 150 mm chord blade specimens in icing conditions, he demonstrated the predicted increasing leading edge surface temperature as the LWC rises until the Ludlam Limit is reached locally and the temperature settles at 0°C. Further increase in LWC widens the chordwise extent of the 0°C region as shown in Fig 2-7 which is a plot of surface temperature against (x/c) at a nominal total temperature of -15°C with LWC in the range of 0-1.0 g/m^3 . Analysis, based on his theoretical model, of the temperature results for tests below the Ludlam Limit, with a freezing fraction of unity, yields local values

of Messinger's relative heat factor b ($= \frac{R_w C_w}{h}$) . These are plotted in Figure 2-8 against LWC and produce straight lines as predicted by the model (Rw is proportional to LWC, whilst h is independent of the cloud condition).

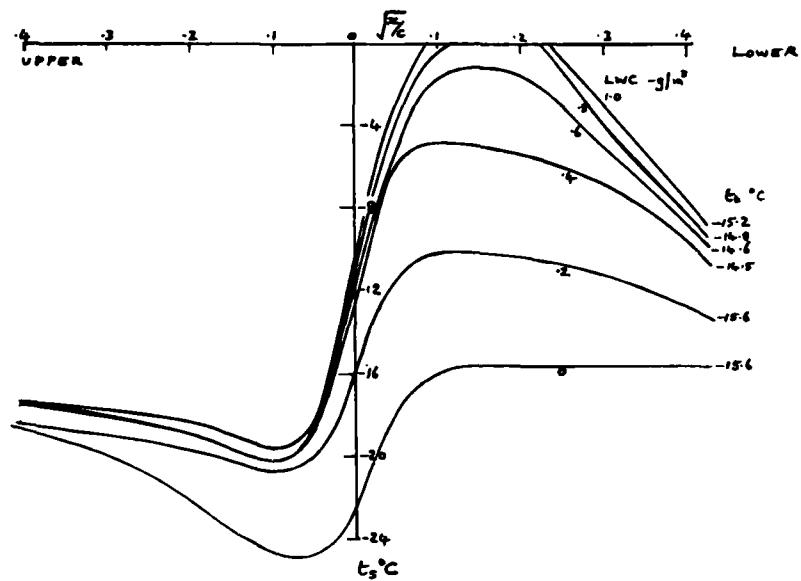


FIGURE 2-7 CHORDWISE VARIATION OF SURFACE TEMPERATURE IN ICING
NACA 0012 $M_\infty = 0.4$ $\alpha = 12^\circ$

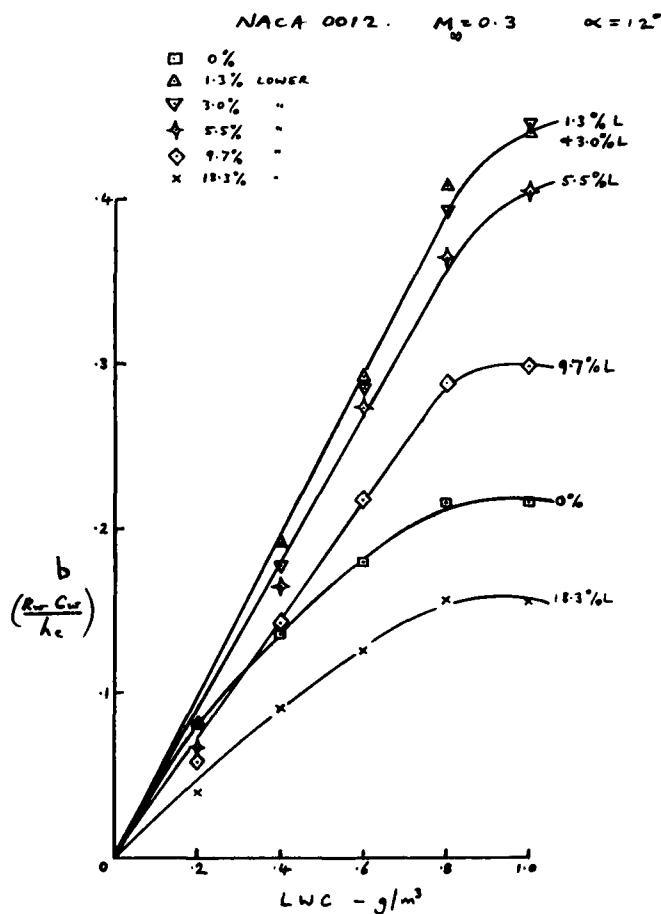


FIGURE 2-8 VARIATION OF DERIVED RELATIVE HEAT FACTOR 'b' WITH LWC

c. Accretion Shapes on Cylinders

The mathematical model developed by Lozowski, et al (ref 2-12) for prediction of ice accretion on non-rotating cylinders and their verification tests substantiate the view that modelling of ice accretion on rotor blades will be possible. Figure 2-3 is an example of the close agreement they obtained between experimental accretion shape and that predicted by their model.

d. Accretion Shape on Aerofoils

Cansdale made observations, during his tests of 150 mm chord specimens, of catch limits and accretion shapes. The former were greater than would be expected on an actual blade owing to the small specimen chord and the use of a 20 μm vmd droplet spray. Comparison of experimental shape and accretion rate with predicted values has not yet been made, but the onset of mushroom growth as Ludlam Limit is approached was observed. He also observed ice formation in the low pressure region on the upper surface of the aerofoils when the stagnation zone surface temperature was above 0°C. This indicates that theoretical study of ice accretion, and also of deicing, must not be confined to the stagnation region alone.

e. Surface Temperature During Deicing

In support of the 1-D thermal transients mathematical model (2.2.4 above), RAE have manufactured three small flat plate heater mat specimens, as shown in Figure 2-9. 50 μm diameter thermocouples were built in at each material interface. A number of tests have been done in still air (natural convection) with the specimens in a deep freeze cabinet both without an ice layer and with a 2.5 mm ice layer frozen on to the top plate. In nearly all the tests, the five elements in each mat were connected in series to give uniform heating over their whole area; also the three specimens were put in series so that the same current was applied to each, giving equal heat intensities.

ALL DIMENSIONS - INCHES

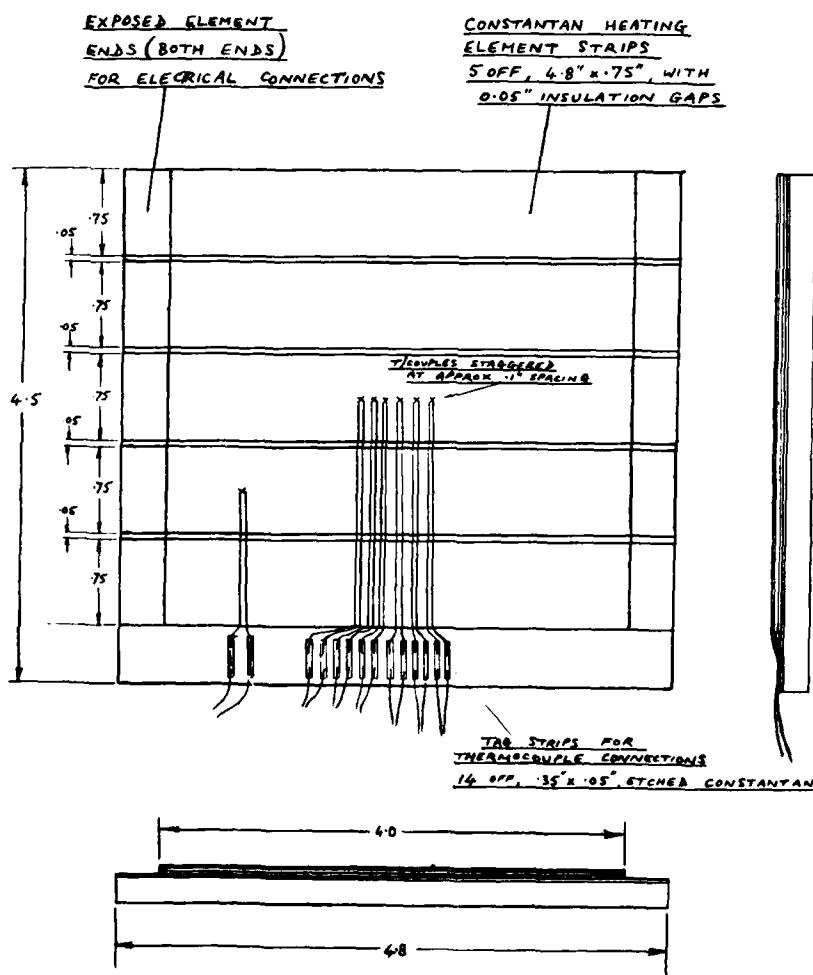


FIGURE 2-9 MULTI-LAYER HEATER MAT SPECIMEN

The parameter of most interest in the tests was the time taken for the ice-metal interface to reach 0°C , i.e., the time required to melt the bond. Figure 2-10 shows a typical trace of this temperature for the three specimens on which it can be seen that the moment of melting is readily identifiable by the change in slope. Figure 2-11 shows typical comparison of theory with experiment for one of the specimens.

FIGURE 2-10 TEST RESULTS WITH MULTI-LAYER HEATER MAT SPECIMEN
(See Figure 2-9)

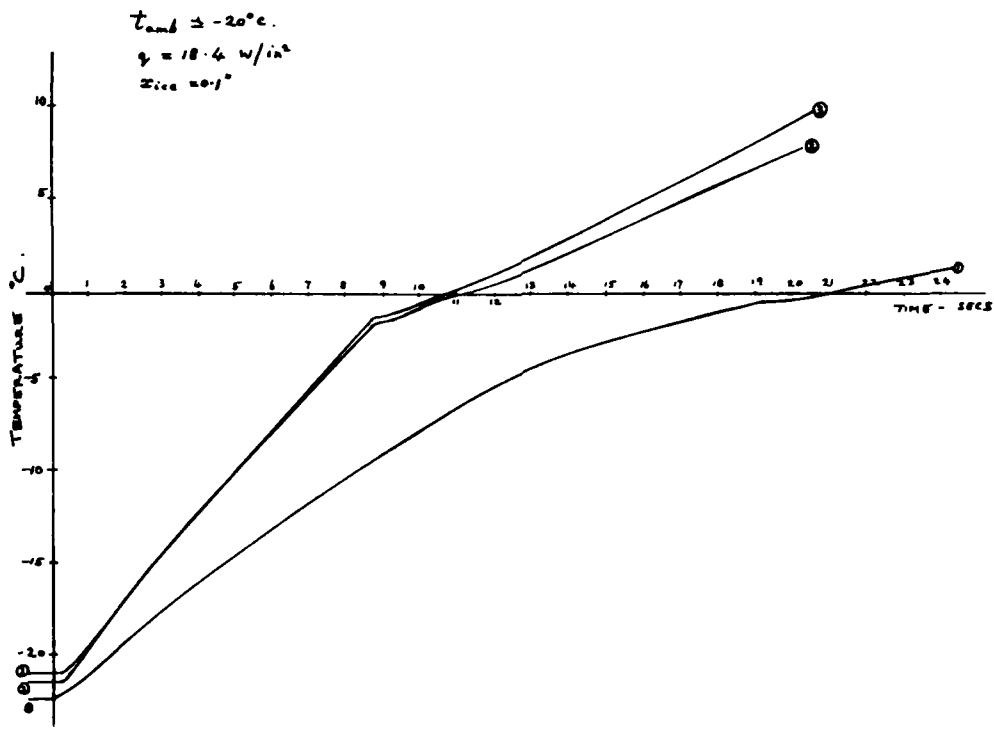


FIGURE 2-10 TEST RESULTS WITH MULTI-LAYER HEATER MAT SPECIMEN

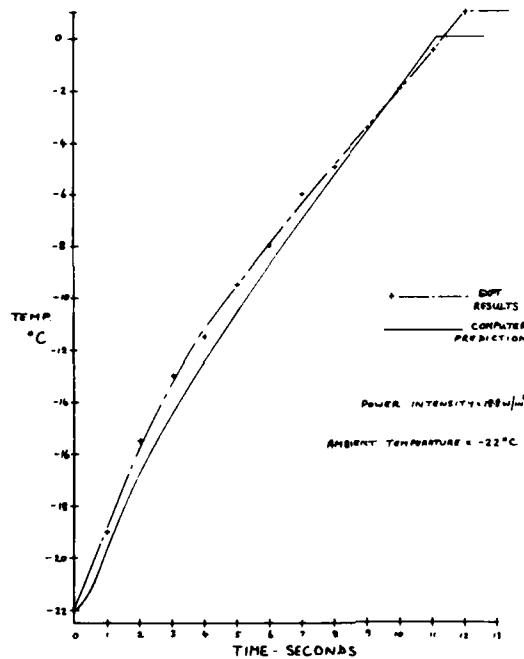


FIGURE 2-11 COMPARISON OF TEST RESULTS AND COMPUTER PREDICTION
FOR MULTI-LAYER HEATER MAT SPECIMEN

The 2-D effect of using only one of the element strips is currently under study and the initial results indicate significant deviation from the 1-D model, thus confirming Stallabrass' opinion that 2-D thermal transient models are required and that the surface temperature above the heater mat insulation gap is a critical factor in achieving satisfactory deicing.

f. Non-rotating Deicing Tests

Tests have been carried out in Cell 3W, NGTE on a 36" long section of Wessex blade fitted with spanwise deicing strips. The blade was mounted in front of a 30" diameter open jet nozzle within the cell, and could be oscillated in pitch at typical blade frequency, i.e., about 250 cycles/min. The blade specimen was fitted with 13 elements of the stamped foil, zig-zag pattern type, each 0.5" wide with 0.05" insulation gaps between, giving chord-wise coverage of about 17% upper to 23% lower. The elements spanned the centre 30" of the blade, corresponding to the blowing nozzle diameter, and were overlaid for about 2" at each end by thermostatically controlled anti-icing mats whose aim was to prevent ice bridging on to the unheated ends of the blade and impeding ice shedding. The deicing elements were supplied via a controller which enabled on-time and heat intensity to be varied and also allowed strips to be grouped to represent the wider elements of a real system. The tests covered a range of Mach numbers from 0.25 to 0.5 at static air temperatures down to -20°C . In general the specification continuous maximum LWC was used, i.e., 0.8 g/m³ at 0°C , 0.6 g/m³ at -10°C and 0.3 g/m³ at -20°C . For most tests the cell pressure was the equivalent of 6000' altitude, although for the highest Mach numbers a lower pressure was used.

The main objective of the tests was to determine whether ice could be shed successfully at all in the absence of centrifugal force and, if it could, over what range of conditions it would shed. If this first stage was successful, the aim was to compare system performance parameters such as optimum on-time and heat intensity and the formation of run-back with results obtained in flight.

The conclusion was that useful testing could indeed be done over a wide range of conditions, and that performance was very comparable with flight data. The main limitation came at low temperatures, as might be expected. For example at a static temperature of -20°C and $M = 0.35$, it became very difficult to shed the ice, even when on-time and intensity were increased. Sometimes shedding would occur every other cycle, or the ice would shed off only part of the span. In general however, at temperatures above about -16°C , the ice could be shed quite cleanly, providing of course that the right cycle, etc., were used. Run-back formations were similar in appearance to those photographed during some flights by the heated rotor blade Wessex, using the rotorhead camera; quantitative comparison of run-back ice is difficult since its thickness cannot be assessed from the flight photographs.

One test was run with the blade at fixed incidence and it was clear that the ice was very much more difficult to shed than in the same conditions with the blade oscillating; it was concluded that the oscillation was an important aid to shedding.

The broad conclusion of the trial was that the technique gave a reasonable simulation of real flight conditions, adequate at least to compare different heater cycles and obtain a first stage optimisation of system parameters.

2.3.2. Rotor Testing: Model and Full-scale

In the course of fixed-wing icing investigations recourse has frequently been made to the use of scale models and the icing scaling laws have been developed and verified experimentally. In the case of Concorde, the position, shape and growth rate of ice accretion on the slender delta wing and engine nacelles were determined in tests at ONERA, Modane, on a 1/6 scale half model of the aircraft. The helicopter rotor, with its span-wise variation in rotational velocity component, severely restricts the scale testing options. Correct simulation can only be obtained by matching the tip and forward speeds of the model and the model rotor rotation rate by the inverse of full scale rotors. Centrifugal force is representative of full scale if similitude laws are respected but the effect on natural shedding of ice from the model due to difference in model and full scale blade dynamic flexibility is largely unknown.

The direction of run back water flow is not fully representative of full scale. Due to the difficulties in producing water droplet sprays with a vmd less than about 10 microns, model scale of less than 1/3 is not possible and a large test facility is required for main rotor testing. In view of the difficulties associated with model testing of main rotors, it is not surprising that there has been only one recorded study, that made on a 1/3 rd scale Puma rotor in the S1 wind tunnel at Modane in which similarities of results with flight test results (ice deposit aspect, increase in torque, decrease of propulsive thrust and lift) were found.

In view of the limited results which can be achieved by model rotor testing and of the expense in producing a fully representative model, it is unlikely that model rotor testing will be widely used as a method of verifying mathematical models. On the other hand, model rotor testing is an attractive way to determine safely the approximate aerodynamic and dynamic degradation of a rotor caused by ice accretion. The cost could be reasonable if the 3 m diameter rotor used by many helicopter companies in their dry wind tunnel tests were used in a large icing wind tunnel, e.g., Modane and IWT.

Full scale rotor testing for mathematical model verification has been mainly limited to rotor surface temperature measurement. Results of studies made in the USA and Germany have been published and tests in the UK on a Puma are planned (Section 2.3.1.a). Tail rotor tests at full scale are feasible in a number of facilities, e.g., IWT and S1 at Modane, and, indeed, were planned by NGTE for Cell 3W but were not made because priority

was given to the main rotor icing problem. An OH-58 tail rotor will be tested by NASA in the IWT in the summer of 1981.

Model rotor testing of electro-thermal deicing systems appears at first sight to be impracticable. Model scaling laws require a change in time scale in the icing condition to achieve correct ice growth rate. This change in time scale will require a compensating change in model heater power if correct simulation of rate of temperature increase and decay at the ice-surface interface is to be achieved. Changes in model heater mat thickness and scaling of the insulation gap between heaters will also put constraints on the model heater power and temperature above the insulation gap is a critical feature. At present it is not known whether these various constraints preclude correct model scale time-temperature simulation: proposals by ONERA to study this problem are strongly supported.

Model testing of ice phobic coatings has been considered in the UK but rejected due to the differences in model and full scale shedding loads and the impracticability of scaling the ice phobic coating.

An alternative to model rotor testing in limited size icing tunnels is testing of truncated full scale sections at reduced rotational radius. This method of testing requires investigation to determine the spanwise range over which adequate simulation of aerodynamic and centrifugal forces and correct ice accretion rate can be achieved. Proposals for studies in this area by NASA together with comparison with non-rotational oscillatory test results are supported.

Full scale section testing at reduced radius was considered in the UK for comparative study of ice phobic coatings but was rejected because of the non-representative variations in spanwise loading in the ice-rotor surface bond.

Full scale rotor testing in the Ottawa spray rig has been done at near hover speeds for a number of years, both for research and for the development of protective systems. In this latter case there are unresolved anomalies: British experience, with the Wessex (ref 2-19), and French experience, with the Puma, indicated that the heating intensity or on/off time relationship with temperature found satisfactory in the spraying rig proved to be unsatisfactory in cruise flight in natural icing conditions. German experience, with the BO 105 (ref 2-20) was that the protection system developed in the spray rig was acceptable in natural icing conditions. The reason for these anomalous results cannot be given with precision but retreating blade stall of the iced blade is more likely to occur at cruise speed than in the near hover condition of the spraying rig and would account for differences in heater off-time. The differences in heater on-time or power density are harder to resolve: one suggestion is that solar radiation heating of the blade could occur in the shallow cloud cover of the spray rig but this cause is not widely accepted. Nevertheless the anomaly is reflected in the views of certifying authorities on the use of the spray rig for certification testing - see section 5. A model rotor run in an icing tunnel over a range of forward speeds could be used to resolve some of the questions of applying spray rig results at higher speeds.

2.3.3. Recommendations

Clearly much work remains to be done before adequate, reliable mathematical modelling of rotorcraft icing is available. The same comment can be made with regard to the icing of fixed wing aircraft upon which the rotorcraft icing analysis is based.

More thought must be given to how detailed the treatment of the rotorcraft flow-field must be in order adequately to model the icing phenomenon. As already indicated, a detailed computation of the rotorcraft aerodynamic environment for no icing conditions present including all interactions is still beyond the state of the art. However it is not clear that such in-depth analyses are required for icing encounter computations.

With regard to the rotor, the adequacy of a two dimensional strip analysis or in turn the need for taking into account the skewed flow velocity component has not been assessed. Similar comments can be made with regard to the required complexity of ice accretion modelling. As already indicated, most of the work done to date regarding droplet impingement and ice accretion has considered the case of an airfoil at fixed incidence and it might be expected that the ice shapes for a rotor blade could be considerably different than the corresponding ones for an airfoil at fixed incidence. In particular, a better understanding of the effects of rotor cyclic velocity and pitch oscillation, rotor flapping, and centrifugal forces on ice accretion must be gained.

Consideration must be given to the more general question of the tolerance of rotor blades to various amounts of the ice growth. If the performance of rotor configurations is significantly reduced by large growths of ice and such large growths can never be tolerated, this can have a significant impact on the direction the modelling process should take.

Answers to the above questions and a resultant improvement in the accuracy of mathematical modelling of rotorcraft icing will come about only after a considerable effort, both experimental and analytical, is expended. The experiments must be defined and dedicated to acquiring the needed information to not only guide the direction of the analysis development but also to evaluate the accuracy of the resultant predictions. Only when the analytical techniques have been demonstrated to adequately simulate the actual rotorcraft icing environment for a wide range of rotorcraft geometries and environmental conditions can the techniques be considered to be truly useful and reliable tools.

In summary, therefore, it is recommended that investigations be made to determine:

- (a) The importance of wake models, skewed flow and the sophistication of model

ice accretions in icing analyses.

(b) The effect on ice formation and shedding of pitch and velocity oscillation, rotor flapping, blade flexing and centrifugal force.

(c) Whether scale model electrothermal deice systems can be developed to be compatible with model icing scaling laws.

(d) The feasibility of truncated full scale rotor icing tests.

(e) A means for interpreting data from tests in hovering rigs (such as Ottawa) in a manner that will allow optimisation of deicing system design.

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3. FACILITIES FOR DEVELOPMENT AND CLEARANCE

3.1 ICING SIMULATION FACILITIES

In all icing simulation facilities the test aircraft or component is located in a cold airstream containing the icing cloud which consists either of supercooled water droplets, solid ice particles or mixtures of the two. The cold airstream is obtained either by using cold ambient air or by using cooling provided by a large refrigeration system. The Icing Cloud Environment (ICE) is made up of very small supercooled droplets (10 to 50 microns diameter) which are produced by special nozzles - generally of the air-assisted atomiser type using high pressure warm air. As the droplets travel in the cold airstream they cool to well below the freezing temperature without freezing (i.e., they supercool). Different nozzles are used to generate the larger droplets of freezing rain (FR). Only a few facilities can produce an airstream containing solid ice particles (SI). The most commonly used method is to feed a large block of ice on to a rotating cutter and to direct the particles produced into the tunnel airstream. This method gives particles of approximately the required size but it is not known how closely they represent those encountered in natural conditions.

The satisfactory simulation of snow has not yet been achieved in spite of a considerable effort, notably at NRC, Ottawa. It is thought that the main reason for this is that the growth of a snowflake in natural conditions takes place over an appreciable time period, and is a process which cannot be simulated in a helicopter test facility. The NRC investigations concluded that tests requiring snow (e.g., engine inlets) could best use natural snow collected from the ground under carefully controlled conditions. It is reported that snow can be produced in the wind tunnel of the Ground Vehicles Test Station in Vienna but no details of the method or the quality of the snow produced are known.

The four basic types of facility and their major variations are shown schematically in Figures 3-1A to 3-1D. The primary differences between each type lie in their geometry, airspeed and kind of tests for which they are used.

The facilities surveyed and their capabilities are listed in Tables 3-1 to 3-7, one table for each of the four types of facilities shown in Figures 3-1A to 3-1D. The North American and European facilities are listed separately. The capabilities of the individual facilities were estimated by the technical contact person for that facility. The figures given in the tables are single point approximations of the facility operating curves. In some instances the capabilities have been truncated to prevent comparisons being made between facilities on the basis of extreme capabilities not relevant to icing tests.

3.1.1 Icing Simulation Facilities in North America

Wind tunnels

The test section leg of a typical icing wind tunnel is shown schematically in Figure 3-1A. Table 3-1 lists the icing wind tunnels in North America. Most are closed tunnels but one is a free-jet (A-5) and is listed in this table because it primarily does wind tunnel type of work. There are ten tunnels now active; another has recently been dismantled (A-4a), and a large high speed altitude wind tunnel has been proposed for 1985. (Alb). One of the high speed tunnels (A4b) will not be available for icing work after 1981.

The test sections of the existing tunnels range from $1.8 \times 2.7m$ for the largest (A-1a) to $0.15 \times 0.10 m$ for the smallest(A-6a). The highest velocity for the larger existing tunnels is 470 Km/h ; two smaller facilities (A-4b and A-5) can achieve $M = 0.8$. Most of the existing tunnels are limited to sea level operation, except for the smaller ones (A-4b, A-5 and A-6b). All but A-9 produce an Icing Cloud Environment (ICE) of adequately small supercooled droplets, including the 20 micron goal. Only a few of the existing tunnels produce the larger droplets of freezing rain (FR); none produces solid ice particles (SI). The LWC range and the cross section of the uniform icing cloud are generally adequate. All these facilities have refrigeration so that they can run at any time of the year; in addition, most are dedicated to full time icing testing.

The existing wind tunnels are ideally suited for research and development type tests. Certification testing at the most severe icing conditions can often be performed, but none of the tunnels can cover the entire FAR 25 envelope or the entire altitude and velocity range of test aircraft. Furthermore, the tunnels are relatively small so that only full scale components of the aircraft can usually be tested (e.g., inlets, tail section, etc.) Helicopter rotors are simply too large. Icing scaling laws are sometimes used to convert tunnel results to the size, airspeed and altitude of the test aircraft but these scaling laws have not yet been adequately verified experimentally.

Engine Test Facilities

Table 3-2 indicates that there are 25 active engine test facilities that can do engine icing tests; in addition, a large engine test facility (B-1c) is planned for 1983. These are all engine test facilities that do icing tests on a test engine as part of the test programme; icing tests account for about 10% of the programme for each engine.

There are two basic types of engine test facilities: the Free-Jet (Figure 3-1B(a)) and the Direct Connect (Figure 3-1B(b)). Many of the engine test facilities can be configured to be run in either mode. In the Free-Jet Mode, the airstream from the blowing nozzle (i.e., the jet) passes around and through the engine. In this way it is possible

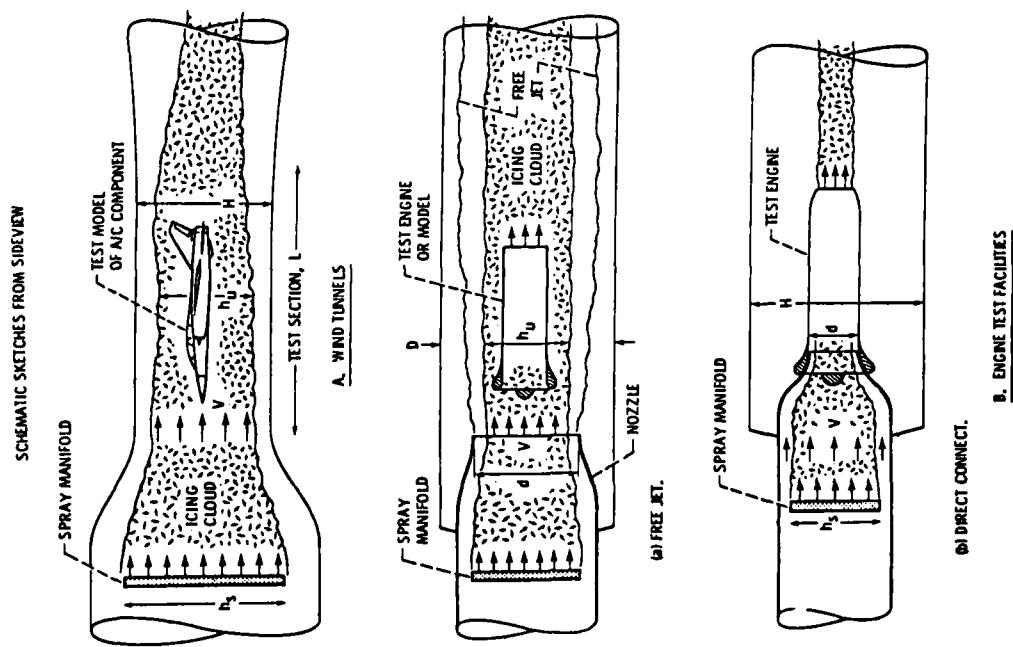
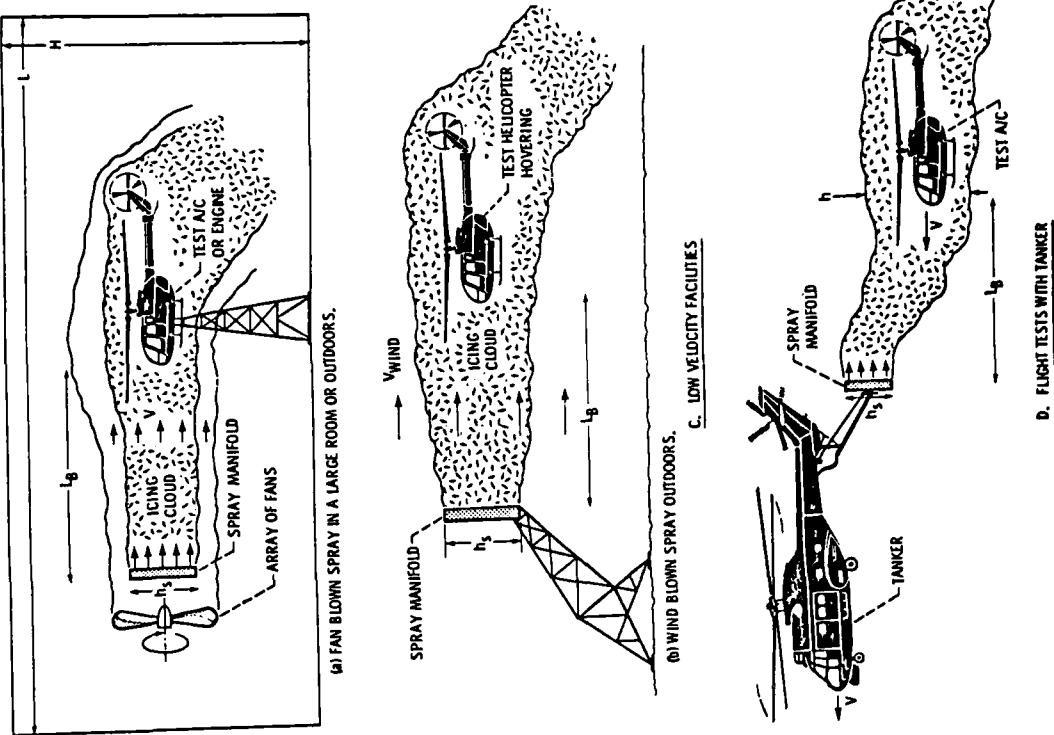


FIGURE 3-1. TYPES OF ICING SIMULATION FACILITIES

to test the engine and its air inlet operating together. In the Direct Connect Mode, the air supply duct is extended up to the engine face so that the entire airstream passes through the engine.

Many of these facilities are large and can attain high airspeeds and altitudes (e.g., B-1a, B-1c, B-5b, and B-6c). The largest of the high speed Free-Jets has a 1.5 m diameter blowing nozzle (B-1b). There is also a very large Free-Jet (B13) but it is limited to very low velocities.

All the engine test facilities produce an icing cloud environment (ICE), but only a few can produce solid ice (SI) particles. Most have refrigeration so that they can be run at any time of year. Comparing the capabilities of the Engine Test Facilities listed in Table B with the Certification requirements indicates that engine Certification tests can be performed in most of these facilities over the entire FAR 25 certification envelope. Free-Jet engine test facilities can be used for many icing experiments that would normally be performed in wind tunnels, especially those with test surfaces that are short enough axially to stay within the potential core of the jet, that is the cone-shaped region of uniform velocity and low turbulence, the tip of which extends some four nozzle diameters from the nozzle exit. The air speed and altitude capability of some of these facilities (e.g., B-1b) are excellent.

Low Velocity Facilities

There are 14 existing facilities listed in Table 3-3, but one may be mothballed in the near future (C-1). All operate at a low velocity and all have freezing rain (FR) capability; the first seven can also produce the Icing Cloud Environment (ICE). Most of the facilities are used mainly for typical cold room tests of equipment in a ground level environment (cold air at low velocity) and aircraft icing tests comprise only a small fraction of their work load. Most of the facilities consist of large refrigerated cold rooms where the test aircraft or component is tied down to the floor and subjected to a fan blown spray (see Fig 3-1C(a)). One of these facilities (C-3a) is large enough to permit a fullscale aircraft to be tested with partial immersion in an icing cloud. Figure 3-1C(a) describes the unique Helicopter Spray Rig (C-1), which is located near Ottawa, Canada. In this case the test helicopter hovers in the wind blown spray. A large engine test facility (C-2) has been included in addition to being listed in Table 3-2. A similar double listing has been made of one very low speed wind tunnel (C-11). On Mt. Washington, equipment is tied down and subject to severe natural icing conditions (C-5). The refrigerated cold rooms can perform icing tests all year, whereas facilities C-1, C-2 and C-5 are essentially limited to winter operation. The LWC and drop size is adequate for ICE or FR tests (whichever is applicable for a given facility).

Tankers for Flight Tests

There are six tankers listed in Table 3-3. Of these one (D-5) has just been added and one (D-1b) is not yet in operation. Most of the tankers are dedicated to full time icing tests.

Figure 3-1D illustrates the principle of all tanker facilities, but only the HISS tanker (D-2) and its test aircraft are helicopters. Individual tankers differ in the shape, size and location of the spray manifold.

Icing tests can be run with most fixed wing aircraft in any season by merely flying at the altitude where the desired temperature occurs, but the limited altitude capability of helicopters limits the icing test season to the winter months.

There have been many problems with these facilities, one of the most serious being large droplets in the spray. The presence of excessively large droplets (of the order of 100 microns) is usually easy to detect because the entire nose of the test aircraft will ice up, whereas small droplets will only cause a small stagnation region on an unheated blunt nose to accumulate ice. Tests were recently performed on the spray nozzles from the Army HISS and Air Force tankers in the NASA IRT (A-1a). The present military tanker nozzles were found to produce droplets that were 2 to 10 times too large, relative to the 20 micron goal. Fortunately, some of the nozzle designs tested produced the desired droplet size at reasonable air and water pressures so that the droplet problem of the entire tanker fleet would seem to be well on the way to a solution. The icing cloud from all the tankers tends to be small and non-uniform, and the test aircraft has to weave about within it; this causes the LWC to vary with time. To account for this a time averaged measurement of the LWC (e.g., an ice accretion measurement) has to be made at the location where the critical ice accretion occurs. There is clearly a need for development of a system giving a larger icing cloud and providing for tests of longer duration. As a target, the cloud should be at least 25 x 9m with at least a 20 minute duration at an LWC of 3g/m³ and one hour at 1g/m³.

Only one of the tankers is readily available. The Flight Systems tanker (D-5) is a recent welcome addition to the fleet, because it is available for hire to all.

With the drop size problem near solution, these facilities should be usable at least for partial certification.

3.1.2 Icing Simulation Facilities in Europe

Wind tunnels

Table 3-5 lists the icing wind tunnels in Europe. Most are closed tunnels but two are Free-Jet (E4 and E7). There are nine tunnels in active operation with one (E2) under reconstruction and due to become available in 1981.

TABLE 3-1 WIND TUNNELS - NORTH AMERICA

SEE TABLE 3-4 FOR NOTES

TABLES 3-1 to 3-7

CAPABILITIES OF ICING SIMULATION TEST FACILITIES

Fa- cility no.	Facility name (location)	Types of icing tests run	Weather stimu- lated	Type of facility	Size (see sketches), m		Range of parameters used in icing tests ^c				Instruments used for local drop size and (LWC)	Technical person to contact	Test es- con- tact	Comment
					Test chamber	Uniform icing cloud	Air speed, km/hr	Min. total air tempera- ture, °C	LWC g/m ³	Vol. med. drop size, μm				
A-1	NASA - Lewis Research Center (Cleveland, OH) (a) IRT	FSC, I MS, R IA, Pd	ICE, FR, FRd	Wind tunnel	H = 1.8 W = 2.7 L = 6	$h_u = 0.9$ $w_u = 1.5$	10 to 470	-30	0	0.5 to 11 to 25 3.0	Rot. cyl. and vari- ation modern instru- ments (rot. cyl.)	J. Reinhardt (216)433-4000	All	Modernization nearly complete
				Wind tunnel	D = 6	$d_u = 4.5$	10 to M = 1.0	-30	0 to 0.2 to 10 to 50 15 000	3.	Various modern instruments (nozzles changed)	J. Yushka (216)433-4000	All	Proposed for 1987
A-2	Lockheed (Burbank, CA)	MS, FSC, I	ICE	Wind tunnel	D = 14	Up to 95					Rot. cyl. (rot. cyl.)	B. Robinson (213)847-6121	All	
A-3	MS, FSC, I	ICE	Wind tunnel	H = 1.2 W = 0.8 L = 0.3	$h_u = 0.5$ $w_u = 0.3$	90 to 340	-20	0	0.7 to 4.0	10 to 25 4.0	Rot. cyl. (rot. cyl.)	R. Wieder (208)342-4776	All	
A-4	NRC (Ottawa, Canada) (a) Large Tunnel	ICE, MS, I, CP, F	Wind tunnel	H = 0.5 W = 0.4 L = 0.9	$h_u = 0.4$ $w_u = 0.3$	180 to 370	-30	0	0.3 to 5.0	10 to 50 5.0 (nozzles changed)	Rot. cyl., oil slide (em. cyl.)	A. Price (613)963-2371	All	
A-5	AEDC Research Cell (Arnold AFS, TN)	FSC, MS	ICE	Wind tunnel	H = W = 0.3 D = 0.3	$h_u = w_u = 0.25$ $d_u = 0.4$ $w_u = 0.3$	90 to M = 0.8	-30	0 to 0.2 to 15 to 25 9 000	2.	Oil slide (rot. cyl.)	A. Price (613)963-2371	All	Also mentioned in 1979
				Wind tunnel	D = 0.9 d = 0.3	$d_u = 0.3$ $M_{jet} = 0.7$	150 to M = 0.7	-30	0 to 0.2 to 15 to 30 15 000	3.	Oil slide (rot. cyl.)	R. DeLeo (612)941-5560	All	
A-6	Rosemount (Minneapolis, MN) (a) Low Speed	MS	ICE	Wind tunnel	H = 0.15 W = 0.1 L = 0.3	$h_u = 0.1$ $w_u = 0.07$	90 to 170	-30	0 to 0.2 to 20 to 40 15 000	0.2 to 1.5	Oil slide (rot. cyl.)	R. DeLeo (612)941-5560	All	Rosemount use only
				Wind tunnel	H = 0.15 W = 0.3 L = 0.9	$h_u = w_u = 0.1$ $d_u = 0.3$	90 to 740	-25	0 to 0.1 to 3 000	0.1 to 3.0	Oil slide (rot. cyl.)	R. DeLeo (612)941-5560	All	Rosemount use only
A-7	Frost Tunnel (Univ. of Alberta, Canada)	MS, IA	ICE	Wind tunnel	D = 0.5 L = 0.9	$d_u = 0.3$ Octogono	10 to 240	-20	0 to 0.4 to 20 to 50 3.0	Oil slide (rot. cyl.)	E. Gates (403)432-5180	All		
A-8	UCLA Cloud Tunnel	MS, CP	ICE, R	Vertical wind tunnel	H = W = 0.15 L = 0.5	$h_u = w_u = 0.1$ -----	0 to 55	-30	0 to 0.1 to 2 to 50 3.	Various modern instruments	H. Propacher (213)825-1038	All	Free particle suspension	
A-9	Army Natick R&D (Natick, Mass.) Climatic Chamber	G, FSC, H	FR, R, S	Wind tunnel	H = 3 W = 4.5 L = 18	-----	4 to 65	-30 to 0	0 to 10 cm rain/ hr	Not measured (rain range)	M. Kelberg (617)653-1000	All	Mainly physiologically tests of humans	

TABLE 3-2
ENGINE TEST FACILITIES - NORTH AMERICA

(Note that most free jets can do wind tunnel types of tests)

No.	Facility name (Location)	Types of icing tests run (a)	Weather simu- lated (b)	Type of facility chamber	Size (see sketches), ^m Test	Air speed Uniform	Min. total air temp °C	Alt- itude m	LWC g/m ³	Vol. med drop size μm	Instruments used for local drop size and (LWC)	Technical person to contact	Test sea- son	Comment
B-1	AEDC (Arnold AFS, (TN). (a) ETF	EDC	ICE	Direct connect $d = 1.5$	$D = 3.7$ or 4.5 $L = 11$	Spray bars sized to engine	0 to $M = 0.7+$	-30	0 to 15000	0.2 to 3+	15 to 30 Various modern Instruments	J. Hunt (615)455-2611	All year	
	(b) Free Jet	CPU,FSC I,MS	ICE	Free jet $d = 1.5$ or 4.5 $L = 11$	$D = 3.7$ or 4.5 $L = 11$	Spray bars sized to engine	0 to $M = 0.7+$	-30 and lower	0 to 15000	0.2 to 3+	15 to 30 Various modern instruments		All year	
	(c) ASTF	CPU,FSC I	ICE	Free jet $d = 2.7$	$D = 8$ $L = 18$	Spray bars sized to engine	0 to $M = 0.7+$	-30 and lower	0 to 15000	0.2 to 3+	15 to 30 Various modern instruments	W. Bates (615)455-2611	All Planned for 1983	
B-2	Detroit Diesel Allison (Indianap- olis, IN) (a) Comp. Test Facility	Inlet and com- pressor stage	ICE	Free jet Direct connect $d = 0.5$	$D = 2.3$ $L = 9$	Spray bars sized to engine	0 to $M = 0.7+$	-30 and lower	0 0 to 6000	0.2 to 3.5	15 to 40 Rotating cylinders	W. Stiefel (317)243-4066	All year	
	(b) Small Engine Facility	EDC	ICE	Direct connect	$D = 0.45$ $L = 1.2$	Spray bars sized to engine	0 to $M = 0.7+$	-30 and lower	0 to 6000	0.2 to 3.5	15 to 40 Rotating cylinders		as above	All year
B-3	GE Cross-wind Facility (Peebles, OH)	CPU,p ^d R ^d	ICE	Free-jet Outdoors $d = 7.0$	$d_u = 4.5$	Ambient air to -20				0.4 to 3.5	15 to 50 Knollenberg spectrometer (rot. cyl.)	R. Keller (513)243-4483	Win- ter	
B-4	P&W Altitude Facilities (E.Hartford, CT)	EDC,I	ICE	Direct connect	$D = 5.5$ $L = 10$	Spray bars sized to engine	0 to $M = 0.5$	-25	0 to 6700	0.2 to 9	0.1 slide	J. Barlock (203)365-2091	All year	
	(b) Smaller	EDC,I	ICE	Direct connect	$D = 3.7$	Spray bars sized to engine	0 to $M = 0.5$	-30 and lower	0 to 6700	0.2 to 9	0.1 slide		as above	All year
	(c) P&W Sea Level Facility	EDC	ICE	Direct connect	Varies with test cells	Spray bars sized to engine	0 to $M = 0.5$	-20	0	0.2 to 9	0.1 slide		as above	Win- ter
B-5	McKinley Climatic Lab. Engine Test Cell (Eglin AFB, FL)	CPU,FSC PR,R	ICE,SI	Fan blown spray indoors	$H = 7.5$ $w_u = 6$ $L = 40$	$h_u = 3$ $w_u = 6$	0 to (30 to 75)	-30 and lower	0 to 3	12 to 60 800 to 1500 (nozzles changed)	Particle Interferometer (rot. cyl.)	R. Toliver (904)882-3626	All year	

B-6	Naval Air Propulsion Facility (Trenton, NJ)	EDC,CPU ICE,SI Free jet H = W = 3 L = 6	Spray bars sized to engine	0 to M = 0.7+ lower	-30 and 0 to 15000	0 to 0.1 to 2	15 to 50 (nozzles changed)	Knollenberg spectrometer and OAP(rot.cyl.)	Resource Manager (609)896-5655	All year
	(a) Five small engine cells	EDC,CPU ICE,SI Free jet H = W = 3 L = 6	Spray bars sized to engine	0 to M = 0.7+ lower	-30 and 0 to 15000	0 to 0.1 to 2	15 to 50 (nozzles changed)	Knollenberg spectrometer and OAP(rot.cyl.)	as above	All year
	(b) Two large sea level cells	EDC,CPU ICE,SI Free jet H = 4.5 W = 7 L = 17	Spray bars sized to engine	0 to M = 0.7+ lower	-30 and 0 to 15000	0 to 0.1 to 2	15 to 50 (nozzles changed)	Knollenberg spectrometer and OAP(rot.cyl.)	as above	All year
	(c) Three large altitude cells	EDC,CPU ICE,SI Free jet D = 5 L = 9	Spray bars sized to engine	0 to M = 0.7+ lower	-30 and 0 to 15000	0 to 0.1 to 2	15 to 50 (nozzles changed)	Knollenberg spectrometer and OAP(rot.cyl.)	as above	All year
B-7	Teledyne Altitude Cells (Toledo, OH)	ICE,SI Free jet D = 2.7 or direct L = 5	Spray bars sized to engine	0 to M = 0.7+ lower	-30 and 0 to 15000	0 to 0.1 to 2	15 to 25 Oil slide	R.Trauth (419)470-3236	All year	
	(a) Chamber 1	CPU,EDC ICE,SI FR,R connect, d = 0.2	Spray bars sized to engine	0 to M = 0.7+ lower	-30 and 0 to 15000	0 to 0.1 to 2	15 to 25 Rotating cylinders	as above	All year	
	(b) Chamber 2	CPU,EDC ICE,SI FR,R L = 4	Spray bars sized to engine	0 to M = 0.7+ lower	-30 and 0 to 15000	0 to 0.1 to 2	15 to 25 Oil slide	R.Trauth (419)470-3236	All year	
B-8	Avco Lycoming (Stratford, CT) (a) Component Facility	EDC ICE,FR connect ----- d = 0.4	Spray bars sized to engine	0 to 370 lower	-30 and 0 to 3	0.1 to 0.1 to 3	15 to 40 Oil slide (rot.cyl.)	J.Sherman (203)378-8215	All year	
	(b) Engine Test Facility	EDC ICE,FR d = 0.4 W = 3.7 H = 2.7	Spray bars sized to engine	0 to 200 lower	-30 and 0 to 3	0.1 to 0.1 to 3	15 to 40 Oil slide (rot.cyl.)	as above	All year	
		d = 1.2 Outdoors								Win-Wint.
B-9	NRC,Cell #4 (Ottawa, Canada)	EDC,CPU ICE,SI Free jet H W 7.5 or direct connect d = 0.75	Spray bars sized to engine	0 to 650 lower	-20 and 0 to 20	0.2 to 0.2 to 2	15 to 40 Oil slide (rot.cyl.)	W.Grafe (613)993-2214	Win-Wint.	
		CPU,P								

SEE TABLE 3-4 FOR NOTES

TABLE 3-3
LOW VELOCITY FACILITIES - NORTH AMERICA

No.	Facility name (location)	Types of icing tests run (a)	Weather simu- lated (b)	Type of facility	Size (see sketches), m	Range of parameters used in icing tests ^c	Instruments used for local drop size and (IWC) μm	Technical person to contact	Test sea- son	Comment		
C-1	NRC Helicopter Spray Rig (Ottawa, Canada)	FLT (helicopters in hover)	ICE, FR	Wind blown spray outdoors	D = ∞	Spray manifold h _s = 4.5 w _s = 23	Ambient wind, 20 to 45 (gusty)	-20 0	0.1 to 30 to 60 0.8	Oil slide (rot. cyl.)	T.Ringer (613)993-2439	Winter To be mothballed in 1983
C-2	G. E. Cross Wind Facility (Peebles, OH)	CPU, P ^d , R ^d	ICE, FR	Free Jet outdoors	D = ∞	d _u = 4.5	90	-20 (ambient)	0.4 to 15 to 50 3.6	KrohnLembeck Spectr. R.Keller	Winter	
C-3	McKinley Climatic Lab (Eglin AFB, FL) (a) Main Chamber	FS, R ^d	ICE, SI	Fan blown spray indoors	H = 21 W = 76 L = 76	Spray manifold h _s = 3 w _s = 9	0 to (30 to 75) (depending on L _B)	-30 and lower	0.1 to 12 to 60 3	Particle 800 to 1500 (nozzles changed)	R.Toliver (904)882-3626	All Largest cold room
(b) Engine Test Cell	CPU, FSC	ICE, SI	Fan blown spray indoors	H = 7.5 W = 9 L = 40	Manifold h _s = 3 w _s = 6	0 to (30 to 75) (depending on L _B)	-30 and lower	0	0.1 to 12 to 60 3	Particle 800 to 1500 (nozzles changed)	as above	All year
(c) All Weather Room	FSC	ICE, SI	Fan blown spray indoors	H = 4.5 W = 6.5 L = 12	Manifold h _s = 3 w _s = 3	0 to (30 to 75) (depending on L _B)	-30 and lower	0	0.1 to 12 to 60 3	Particle 800 to 1500 (nozzles changed)	as above	All year
C-4	US Army CREL Cold Room (Hanover, NH)	FSC, MS R, LA	ICE, SI	Fan blown spray indoors	H = 1.1 W = 0.7 L = 1.5	0 to 20	-30 and lower	0	1 to 10 to 60 2.5	Cascade impactor	G.Ashton (603)643-3200	All year
C-5	Mt. Washington Observatory (Gorham, NH)	FSC, CP MS	Natural icing of tied down equipment on top of mountain		0 to 180 (gusty)	-20 and lower	1800	Generally severe natural conditions	Rotating cylinders	J.Howe (603)466-3388	Fall to spring	
C-6	US Navy PMTC (Pt. Mugu) Climatic Hangar	FSC, FS G	R, FR S	Fanblown spray indoors	H = 7.6 W = L = 1.2 = 18	0 to 75	-30 and lower	0	30 cm 500 to 4500 5 cm snow/hr	Oil slide (rain gauge)	D.Everett (805)982-8011	All year
C-7	Acton Environmental Test Corp. (Acton, MA)	G	R, FR S ^d	Fanblown spray indoors	H = 6 W = 4.5 L = 7.5	d _s = 2.5	0 to 45 -30 and lower	0	10 cm 1000 to 4000 rain/hr	Not measured (rain gauge)	R.Gilfoyle (617)263-2933	All year

C-8	NRC (Ottawa, Canada) Cold Chamber #1	G, FS	FR, S ^d	Fan blown spray indoors	H = 4.3 W = 4.5 L = 15.2	d _s = 1.2 to 2.5	0 to 55	-30 and lower	0	0.3 cm rain/hr	500 to 1000	Screen method (accumulation rate)	T. Ringer (613) 993-2439 All year
Cold Chamber #2	G, FS	FR	Fan blown spray indoors	H = 5 W = 5 L = 7	d _s = 1.8	0 to 55	-30 and lower	0	0.3 ^d cm rain/hr	500 to 1000	Screen method (accumulation rate)	as above	All year
C-9	Wyle Labs (Norco, CA) Cold Room	G, FSC	FR	Fan blown spray indoors	H = 5 W = 4.5 L = 11	----- 0 to 35	-30 and lower	0	12 cm rain/hr	-----	-----	M. Clark (714) 737-0871	All year
C-10	Arctec Canada Ltd (Ottawa, Canada) Cold Room	G, IA	FR ^d , S ^d	Fan blown spray indoors	H = 3.7 W = 5.5 L = 9	----- 0 to 35	-30 and lower	0	-----	-----	-----	A. Nawar (613) 592-2830	All year

SEE TABLE 3-4 FOR NOTES

TABLE 3-4
TANKERS FOR FLIGHT TESTS - NORTH AMERICA

(In addition, most airframe companies can test aircraft in natural icing)

No.	Facility name (location)	Types of icing tests run (a)	Weather simu- lated (b)	Time in icing at high LWC min.	Size of spray, m	Range of parameters used in icing tests ^c	Instruments used for local drop size and (LWC)	Technical person to contact	Test season (find temp at altitude)	Comment
D-1	US Air Force (Edwards AFB, CA) (a) KC 135 Tanker	ICE, N R, FR Flt	At $L_B = 60$ $d = 3$	$d_s = 1.2$ 300 to 650 (370 nom.)	-20 1200 8000	0.05 to 1.5 to 32	Knollenberg spectrometer (")	R. Morrison (805)277-3068	All year	Final calib- ration in 1981
	(b) C 130 Tanker	Flt R, FR	At $L_B = 60$ $d = 5$	$d_s = 1.2$ 190 to 390 (280 nom.)	-20 1200 8000	0.05 to 1.5 to 32	Knollenberg spectrometer (")	as above	All year	Planned for 1981
D-2	US Army HISS Helicopter Tanker (Edwards AFB, CA)	ICE, N Flt	At $L_B = 50$ $h = 3$ $w = 12$	$h_s = 1.6$ $w_s = 12$	110 to 140 (120 nom.)	-20 600 3500	0.1 to 25 to 1.0 desired	Knollenberg spectrometer (Leigh)	C. Franken- berger (805)277-2271	Normally winter cloud size
D-3	Cessna 404 Tanker (Wichita, KS)	ICE, R FR, N Flt	At $L_B = 150$ $d = 6$	$d_s = 0.6$ (V-bar)	165 to 330 (260 nom.)	-20 300 8000	0.05 to 4.0 nozzles	Gelatin slide (J&W)	D. Hazelwood (316)946-6606	All year
D-4	Piper Cheyenne Tanker (Lock Haven, PA)	ICE, FR R, N Flt	At $L_B = 30$ $h = 3$ $w = 5$	$h_s = 1.2$ $w_s = 1.8$	200 to 300 (240 nom.)	-20 300 8000	0.1 to 30 to 1.7	Gelatin slide (J&W)	J. Bryerton (717)748-6711	Not summer
D-5	Flight Systems T-33 Tanker (Mojave, CA)	ICE, R FR, N Flt	At $L_B = 60$ $d = 2.5$	$h_s = 0.3$ $w_s = 0.9$	230 to 420 (370 nom.)	-20 300 8000	0.1 to 17 to 1.0	Knollenberg spectrometer (")	J. Lilison (805)824-4601	All year

NOTES

^aTypes of icing and anti-icing tests run: CPU = complete propulsion unit; EDC = engine direct connect; FSC = full-scale aircraft component (including wing, tail, fuselage, windshield, stores, gear, etc.); MS = model scale tests and instrumentation; IA = ice adhesion; CP = rotating experiments (e.g., helicopter rotor models and propellers); G = ground transport and installations in freezing rain; FS = full scale aircraft; Flt = flight tests of aircraft; I = inlets with suction; P = complete propeller engines; H = human physiological experiments.

^bWeather simulated: ICE = icing cloud environment; SI = solid ice particles; FR = freezing rain; R = rain; N = natural icing; S = snow.

^cParameter ranges vary with conditions; request operating envelope from contact person.

^dModification to do this has been seriously proposed.

^eTests in progress to extend these limits.

The test sections range from 8 m diameter for the largest (E6) to 0.5 x 0.5 m (E10) for the smallest. Most are limited to sea level operation, but two (E5 and E6) run at altitude. The highest velocity for the larger tunnels is 540 Km/h; one of the smaller tunnels (E5) can reach 900 Km/h.

With two exceptions the tunnels can be run at any time of year. The exceptions (E6 and E9) require low ambient temperatures to achieve the required test conditions, additional cooling being obtained in the case of E9 by the injection of liquid nitrogen into the airstream. This generates fog which partly obscures the test vehicle but the deposition and accretion of ice may not be significantly affected.

Engine test facilities

Five facilities that can do icing tests are listed in Table 3-6. They can all undertake direct-connect icing tests on engines at any time of year and the larger facilities can test aircraft components on engine air inlets. The largest facility (F4) can test the front fuselage of a medium size helicopter (e.g., Lynx or Sea King) at conditions representing forward flight (i.e., where rotor downwash effects are minimal). From 1981 this facility will also have the capability of producing an icing environment containing solid ice particles either alone or in combination with supercooled water droplets.

Engine certification tests can be performed in all these facilities over the FAR 25 envelope.

Tankers for flight tests

Only one tanker is listed in Table 3-7, the Canberra operated by A&AEE, Boscombe Down. This tanker has not however been used for helicopter icing tests because its minimum flight speed is rather too high.

3.2 EVALUATION OF ICING SIMULATION FACILITIES

In this section the adequacy of existing icing simulation facilities is reviewed, deficiencies cited and where appropriate short term corrective measures briefly discussed. The main types of icing test undertaken on helicopters are listed below:

Types of Icing Test

A. R&D and Certification tests

A(i) Engines

A(ii) Instruments

A(iii) Helicopter components, (including ice protection systems for engine inlets and main rotor blades)

B. General research and technology development

3.2.1 Facilities to Test Instrumentation

There are several small government and company facilities both in North America and in Europe for R&D or certification tests on icing instrumentation, (e.g., A-4b, A-5, A-3, A-7, E5 and E10). Larger facilities can often run instrumentation tests in parallel with another test at little or no additional cost.

3.2.2 Engine Test Facilities

Tables 3-2 and 3-6 indicate that there are many engine test facilities that can do icing tests and most of these have excellent capabilities for testing engines over the whole FAR 25 envelope. There is however one obvious deficiency in that very few facilities can generate solid ice particles.

Most of the engine test facilities can undertake free-jet tests of the engine running behind its inlet. Such tests enable the inlet anti-icing system to be developed and the optimum location of the heater mats or other heat input systems to be defined and their performance established.

In the larger facilities, for example Blb, F1, F4, it is possible to test engines with their inlets installed in part or whole of the front fuselage. In this way the surrounding flow field can be simulated. This is an important advantage since the flow curvature exerts a powerful influence on the local water concentration at the inlet by virtue of the effects of momentum separation.

3.2.3 Facilities for Helicopters

Performing natural icing tests on complete helicopters is extremely costly because of their very limited range and altitude. Therefore icing simulation facilities are needed for the bulk of the tests to supplement natural icing tests including the certification tests. The engine and fuselage can be readily handled (except for the aerodynamic effect of the rotor) by existing engine test facilities and by the facilities used for fixed wing aircraft, but icing tests on a full scale rotor can be conducted in only a few of the existing icing facilities because of its very large size. Helicopter rotors have diameters ranging from 10 to 25 m so that a wind tunnel some 15 to 38 m across would be required for proper aerodynamic representation. The icing cloud spray bar of a simulation facility should ideally be about the size of the rotor (up to 25 m across).

TABLE 3-5
WIND TUNNELS - EUROPE

No	Facility Name Location	Types of Icing Tests Run (a)	Weather Simulated (b)	Type of Facility	Size		Range of Parameters used in Icing Tests					Technical Person to Contact	Test Season	Comment	
					Test Chamber m	Uniform Icing Cloud m	Maximum Air Speed km/h	Min Total Air Temp °C	Altitude m	LWC g/m ³	Vol Med Drop Size μm				
<u>Austria</u>															
E1	Ground vehicles test station. Vienna	ICE	Wind Tunnel 4.9 x 4.9				115	-18	0					To date tests on cars & railway vehicles	
<u>Federal Republic of Germany</u>															
E2	Volkswagen Wolfsburg		Wind Tunnel 5 x 7				180	-25	0			Hr Schwab 05361-225130	All Year	To date only on cars	
E3	DFVLR		Wind Tunnel 2.4 x 2.4				290-320	-173	0			Dr Viehweger 02203-6012295	Under reconstruc- tion. Icing tests possible 1981		
<u>France</u>															
E4	Etat Technique Bourges	FS MS	ICE FR	Wind Tunnel H = 4.1 W = 5.5 L = 15			145	-40	0			A, B	IPETA Chastagnol (48) 70 52 75	All Year	
E5	CEFR Saclay	MS	ICE	Wind Tunnel D = 0.25 D = 0.9			$\frac{d_u}{d_u} = 0.25$ $\frac{d_u}{d_u} = 0.9$	900 290	-15 -40	0.1-3 0.1-3	15-30 15-30			M Page- Galtier (6) 941 81 50	All Year
E6	ONERA Modane	FS MS R	ICE	Wind Tunnel D = 8			$\frac{H_u}{W_u} = 2$ $\frac{H_u}{W_u} = 2$ or = 4	540	-15*	1100- 2500	0.4-10 10-30	Various	C Armand (79) 05 00 55	Winter depends on ambient condi- tions	

<u>Italy</u>								
E7	R	SI FR	Wind Tunnel	H = 3 W = 4.2 L = 11.6	140	-50	0	
Fiat Research Centre Turin								
<u>Sweden</u>								
E8	Aero- nautical Research Institute		Wind Tunnel	D = 3.6	145	0		
<u>United Kingdom</u>								
E9	A&AEE Blower Tunnel Boscombe Down	FS MS	ICE	Wind Tunnel Open Bed	d = 1.2 d = 1.8	500 400	-30	0
E10	Lucas Aerospace Arlington	MS	ICE SI FR	Wind Tunnel	H = 0.2 W = 0.3 to H = 0.5 W = 0.5	660 215	-40	0

SEE TABLE 3-7 FOR NOTES

A Garros
(011) 9012777
Ext 139

All
Year

Tests on
simu-
lated ice
accretion
shapes

Winter
LN₂
injection
for
cooling

Supt of
Enggneering
(0950) 23331

20-1000
A, C

12-40
0.1-5
0.2-10
1mm
ICE

A, D

G Bagington
(0483) 68876

All
Year

TABLE 3-6
ENGINE TEST FACILITIES - EUROPE

No Facility Name Location	Types Of Icing Tests Run (a)	Weather Simulated (b)	Type of Facility	Size		Range of Parameters used in Icing Tests					Technical Person to Contact	Test Season	Comments
				Test Chamber m	Uniform Icing Cloud m	Maximum Air Speed km/h	Min Total Air Temp °C	Altitude m	LWC g/m ³	Vol Med Drop Size μm			
France													
F1	CEPr Saclay R2 cell	CPU FS	ICE	D = 4.4	$d_u = 1.15$	540	-60		0-6	15-30	A	M Fage-Galtier (6) 94.1 81 50	All Year
F2	CEPr Saclay R6 cell	CPU FS	ICE	D = 5	$d_u = 3$	260	-60		0-10	15-30	A	M Fage-Galtier (6) 94.1 81 50	All Year
United Kingdom													
F3	NGTE Pyestock Cell 3	EDC CPU	ICE SI	D = 6.1	Engine dia or $d_u = 1$		-70	0-15000	0.2-10	15-30	D	Head Engine Test Dept (0252) 44411	All Year
F4	NGTE Pyestock Cell 3 West	EDC CPU FS MS	ICE SI FR	D = 7.6	Engine dia or $d_u = 2.5$		-40	0-15000	0.2-10	15-30	D	Head Engine Test Dept (0252) 44411	All Year
F5	Lucas Aero- space Burnley	EDC MS	ICE SI	D = 4	Direct Connect or Free Jet		-55	0-15200	0.2-10	15-30	A	Mr B A Coar (0282) 25051	All Year

SEE TABLE 3-7 FOR NOTES

TABLE 3-7
TANKERS FOR FLIGHT TESTS - EUROPE

No Facility Name Location	Types of Icing Tests Run (a)	Weather Simulated (b)	Size		Range of Parameters used in Icing Tests				Instruments Used for Local Drop Size and LWC (c)	Technical Person to Contact	Test Season	Comment
			Uniform Icing Cloud m	Air Speed km/h	Min Total Air Temp °C	Altitude m	LWC gm/m ³	Vol Med Drop Size μm				
United Kingdom												
Canberra W787 icing tanker A&AE Boscombe Down	FLT	ICE N			H _S = 6 W _S = 12	270 to 675	Local ambient	Up to 12000	0-3	30-40 A, C	Supt of Engineering (0980) 23331	All Year Facility fully tested

NOTES:

a. Types of icing test run

CPU = complete propulsion unit; EDC = engine direct connect; FSC = full scale aircraft components; MS = model scale tests; R = rotating experiments;
FS = full scale aircraft; FLT = flight tests of aircraft.

b. Weather simulated

ICE = icing cloud environment; SI = solid ice particles; FR = freezing rain; N = natural icing.

c. Instruments used for drop size and LWC

A = oiled slide; B = Rogeo spectrometer; C = Johnson and Williams moisture concentration meter; D = other devices (eg Knollenberg).

Aerodynamic tests of scale model rotors (about 1/10 scale) are commonly performed, but there is little background of experience with icing tests on scale model rotors. One reason is that the minimum droplet size produced by simulation facilities is too large. Limited measurements with old-style instruments suggest that the minimum VMD is about 10 microns. Figure 3-2 indicates that the smallest model that could be tested, scaled correctly to a full scale aircraft in a 20 micron natural cloud, would be a 1/4 scale model. The largest existing icing wind tunnel in North America (Ala) could accommodate a 1.5 m diameter rotor. This represents a 1/12 scale model of the CH-47 or a 1/6 scale BO 105. Either model would require a tunnel spray system that could produce droplets less than 10 microns diameter and this is not currently possible.

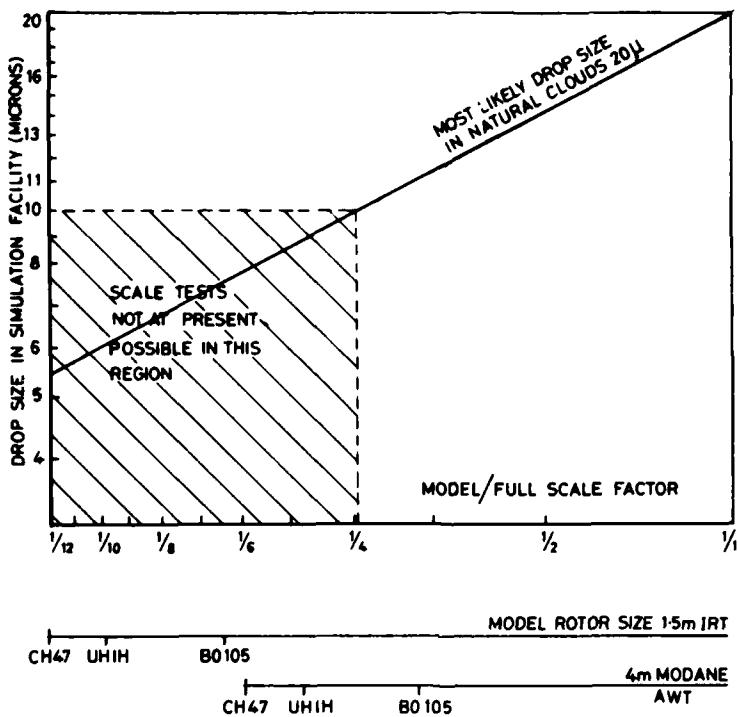


FIGURE 3-2 EFFECT OF DROPLET SIZE (VMD) ON SCALING

Some tests have been done in France, using the large wind tunnel at Mondane (E6) with a 4 m rotor diameter and 10 micron droplets VMD. Although similarities of results with flight test results were found, it is fair to say that insufficient data exist to enable the scaling laws to be adequately verified. The background to using scale models for icing tests is discussed in more detail in Section 2.3.2.

In the near term, Certification and R&D tests would use a combination of ground and flight facilities, along with a minimum of natural icing flight tests. In order to determine the proper mix, experiments are needed to ascertain which simulation facilities correctly simulate natural icing on helicopter rotors. For example, the HISS tanker, until recently, generated icing clouds with droplets that were appreciably larger than those of natural icing; as a consequence the ice accretions were closer to those produced by freezing rain. The new spray nozzles for the HISS give results which are closer to those obtained in natural icing conditions. The Ottawa Spray rig is thought by some countries to be a useful facility but it is limited to helicopter operation in hover conditions in light winds and it relies on natural ambient temperature. Verification is also required for model scale and truncated rotors on a rotating rig and also for oscillating blade tests. After these verification experiments are complete, the mix of facilities required for Certification and R&D tests would be known. The rehabilitated AWT of NASA (A-1b) may be added to the list of facilities when available in about 1985 because it offers the prospect of testing large scale models at low cost.

3.3 FACILITIES FOR NATURAL ICING TESTS

Unlike large fixed-wing aircraft, helicopters have limited range, endurance, climb capabilities, and service ceilings. This is true for most of today's helicopters and those likely to be developed in the next few years. These limitations require a different set of ground rules for the conduct of natural icing flight tests both for research and for certification purposes.

Large fixed-wing aircraft can be subjected to a large variety of natural icing test conditions during one winter test season. This is possible because the test aircraft can usually be based at the manufacturer's own plant where all necessary support is available, fly to prevailing weather conditions, conduct the required testing, and return.

This is customarily done in one day's operation, and sometimes may entail flights of several thousand miles in one day. Aircraft of this type also have the ability to take advantage of icing conditions that may exist in the upper extremities of cumulus-type clouds that often contain high liquid water contents and the lower extremes of ambient temperatures.

The helicopter has a very different problem. Test helicopters, because of limited range, endurance, airspeed and service ceiling, must be prepositioned at test sites in geographical regions where icing conditions are prevalent. Most commonly, the test site selected is many miles away from the manufacturer or test agency's facility. This dislocation is costly in many respects, so the site selection must thoroughly consider many variables to assure that maximum benefit is obtained from the investment.

The Rotorcraft Icing Working Group has taken advantage of past experience of the North Atlantic Treaty Organization member nations to develop a list of site selection parameters that are important to consider during the natural icing test planning phase. This list, along with characteristics of test sites used by various member nations, is contained in Table 3-8. The following paragraphs discuss the various site selection parameters:

Atmosphere

The classical icing test for certification purposes dictates that a large percentage of the weather conditions will consist of cloud types and ambient temperatures that produce supercooled cloud icing conditions. The frequent existence of these conditions is paramount for natural icing tests.

In addition, specific testing in snow conditions is sometimes required to verify tolerance of certain components to the snow environment. It is also speculated that, in the future, freezing rain and drizzle conditions will be required to allow testing to be performed to at least determine remedial actions, if not to establish operational/flight limitations of the helicopter in these conditions. Only limited flight testing has been conducted to date in freezing rain or drizzle conditions.

Use of long-term statistical data is considered the only accurate method of determining the probable frequency of occurrence of various weather conditions. However, caution is advised. Statistical data (long-term) will not assure that average conditions will prevail during any one test season. If at all possible, alternate natural icing test sites should be selected and decision points made to move the test operation from the primary site to provide the flexibility needed to assure a successful test season. On-site test managers must have the authority and the resources to make this decision to allow maximum utilization of prevailing weather conditions.

In the United States (US), the National Weather Service (NWS) and the US Air Force (USAF) Environmental Technical Application Center are repositories for long-term statistical data on which to base natural icing test site selections. Requests for specific information must be submitted far enough in advance to allow these agencies time for the necessary compilation. Data requests are usually required to be submitted in writing; however, face-to-face, or at least telephone, discussion with the agencies' personnel is highly encouraged to assure a thorough dialogue and understanding of the specific questions being asked and the data being provided in response to those questions.

Key parameters to be considered are listed in column 2 of Table 3-8. These parameters are self-descriptive for the most part. Cloud ceiling, however, is a parameter that has been overlooked in the past. Specific attention to early establishment of the cloud ceiling and visibility requirements stipulated for flight safety, cloud egress, and rescue purposes is encouraged. These limits must be established prior to submitting a request for data.

Airspace

The natural icing test site selected must be compatible with the communications and navigation capability of the test aircraft.

Airspace Allocation

Weather systems in many instances are scattered or very localized. The test team cannot rely upon one established small boundary in a local test area, but must seek authority to conduct natural icing testing anywhere within the safe operational range of the aircraft to enhance the probability of a successful test season. Prior authority must be negotiated and obtained from the local air traffic control (ATC) authorities. Again, face-to-face discussion with the affected ATC officials, airport managers, tower operators, other organized local operators, and, in some localities, civic leaders is required.

Navigation Aids

These must be compatible with the test aircraft.

Ground Radar

Two considerations are important: (1) availability of ground radar for traffic avoidance; and (2) vector information to supplement other navigation aids and for use in emergencies to vector a rescue aircraft to the site of a downed aircraft. Radar deflection and usable altitude limitations in proposed test areas become important considerations.

Communications

It is essential that radio communications exist, not only with ATC, but with the aviation weather service in addition to normal communications between the test aircraft,

TABLE 3-8. SITES FOR NATURAL ICING TESTS

	<u>OTTAWA</u> Canada	<u>BRETIGNY</u> France	<u>TIRSTRUP</u> Denmark
ATMOSPHERE			
Cloud Cover	Known	Known	Known
Temp. and IWC Data	Temp. and Dew Pt.	Temp. and Dew Pt.	Temp. and Dew Pt.
Snowfall	Known	Unknown	Known
Snow Cover	Known	Known	Known
Hours of Daylight	Known	Known	Known
AIRSPACE			
Allocation	Defined and Limited	Unlimited (ATC)	Unlimited (ATC)
ATC Liaison	Special	Special and IFR	Special and IFR
Navigation Aids	TACAN, VOR, ILS	VOR, ILS	TACAN, VOR, ILS
Radar Coverage	Altitude, Limited	Available	Altitude, Limited
Communications	VHF, UHF	VHF, UHF	VHF, UHF
Meteorology	Available	Available	Available
Traffic Density	Constraint	No Constraint	No Constraint
Population Density	Light		
SEARCH AND RESCUE			
Topography	Flat 180°	Flat 360°	Flat 360°
Services	Normal and Local AF	Normal and Local AF	Normal and Local AF
Equipment	Helicopters	Helicopters	Helicopters
TEST SUPPORT			
Aircraft Shelter	Heated	Heated	Heated
Engineering	Known	Known	Known
Office Space	Adequate	Adequate	Adequate
Power Supplies	Known	Known	Known
Data Processing	Known	Known	Known
Logistics	Known	Known	Known
TELEX Facilities	Available	Available	Available
POL	Available	Available	Available
SECURITY CLEARANCE			
Military Aircraft	Required	Required	Civil Registration
Crew	Required	Required	Spec. Authorization
Civil Aircraft	Required	Required	Danish Civil Authority
Special Instr.	Required	Required	Spec. Authorization
DOMESTIC			
Accommodations	Adequate	Adequate	Adequate
Catering	Adequate	Rental	Adequate
Transportation		Rental	Rental
Entertainment		Poor	Poor

TABLE 3-8 (continued).

	<u>MANCHESTER</u> England	<u>ST. PAUL</u> U.S.	<u>SYRACUSE</u> U.S.
ATMOSPHERE	Cloud Known Temp. and LWC Data Known Snowfall Known Snow Cover Known Hours of Daylight Known	Temp. and Dew Pt. Known Temp. and Dew Pt. Known Temp. and Dew Pt. Known Temp. and Dew Pt. Known	Known Known Known Known
AIRSPACE	Allocation Limited ATC Liaison Good Navigation Aids Sufficient Radar Coverage Good Communications Good Meteorology Good Traffic Density High Population Density High	Normal ATC IFR TACAN, VOR, ILS Altitude Limited VHF, UHF Minn/St. Paul Airport Constraint Moderately High	Normal ATC IFR TACAN, VOR, ILS Altitude Limited VHF, UHF Minn/St. Paul Airport Constraint High
SEARCH AND RESCUE	Topography Better than Alps Services Available Equipment Available	Rolling and Streams 180° Air Nat'l Guard Helicopters	Flat 360° Army Reserve Helicopters
TEST SUPPORT	Aircraft Shelter Heated Engineering Available Office Space Adequate Power Supplies Available Data Processing Available Logistics Some Available TELEX Facilities Available	Heated None Adequate Limited Commercial Minimal Available	Scarce, Heated None Poor Limited Photo Processing None Commercial
SECURITY CLEARANCE	Military Aircraft NATO Base Crew NATO Base Civil Aircraft NATO Base Special Instr. NATO Base	Local Civil and Mil. Author. Local Civil and Mil. Author. Local Civil and Mil. Author. No Restriction	Airport Authority No Restriction Airport Authority No Restriction
DOMESTIC	Accommodations Ingolstadt Catering Adequate Transportation Adequate Entertainment Good	Motels Adequate Rental and GSA Adequate	Adequate Adequate Rental Adequate

chase or crash rescue aircraft, and the base of test operations. It is also highly desirable to have telephone communications with each of the service agencies (ATC, weather, tower).

Traffic Density

Icing tests must of necessity be conducted under adverse weather conditions. If a busy airport is selected as the base of operations, test capability can be extremely limited by ATC because of other traffic either in departure or approach, or in achieving clearance for flight at various test altitudes within the control zone. The ability to climb or descend in the event of a problem is also encumbered. It becomes highly desirable to select a test area where traffic density is as small as possible.

Population Density

Remote areas are always desirable for any test purposes; however, their use is not always possible. Several key problems must be considered during the site selection process. The possibility of an inflight accident is paramount. During icing tests, particles of ice can be shed from the test aircraft and could be hazardous in populated areas, either to personnel or structures. Special attention must be given to these considerations in final approach and test recovery areas.

Emergency Landing Sites

Emergency landing sites must be available in flight test areas. In addition, topography must not inhibit search and rescue operations.

Aircraft Support and Test Support

Adequate support of the test aircraft is essential during the conduct of helicopter natural icing tests. The test helicopter should normally be equipped with instrumentation for flight test data acquisition. Hangar, laboratory, and office facilities must be available, not only for aircraft shelter, but also to support normal aircraft maintenance and inspection; instrumentation maintenance, checkout, and calibration; and data processing, data reduction, and analysis. Data processing may require availability of local, commercial computer facilities that must be compatible with test aircraft instrumentation tapes or recordings. To assure this compatibility may require extensive coordination during the test planning phase.

Most test helicopters will be equipped with ice detection and ice protection systems that are in the experimental, developmental, prototype stages of development. Aircraft support facilities should accommodate the needs for inspection, maintenance, checkout, calibration, troubleshooting and repair of these systems. Engineering and maintenance capability/expertise must also be available to perform these functions. Of particular importance is the availability of ground power units of the proper size and compatible with the test aircraft that are approved for hangar operation for use in ground checkout and troubleshooting or electrothermal type ice protection systems.

In some tests, requirements exist for dedicated crash/rescue or chase aircraft. Aircraft shelter, logistical support, and maintenance support of these aircraft become essential considerations. In most regions in which natural icing test sites would be considered, surface temperatures are usually very cold. If the hangar is heated, as it should be for adequate test support, many hangar custodians have rigid door opening schedules for energy conservation purposes or may impose door opening fees to offset heating costs. This becomes an important consideration during the site selection process.

Domestic Considerations

The process of selecting a natural icing test site must consider the human element and assure that accommodations for lodging, dining, transportation and entertainment are adequate commensurate with the test duration. The availability of recreation rooms near the work area has been shown to be beneficial. Another important consideration is the establishment and adherence to a firm go-home date. This should be carefully established to assure that productive testing can be achieved by the date specified.

3.4 REQUIREMENTS FOR FUTURE FACILITIES

The Working Group has confirmed that many types of icing test facilities are available both in North America and in Europe. Each type of facility has its particular part to play and to cover the full range of helicopter icing problems several different types - wind tunnels, engine test facilities and flight test - need to be employed.

In North America the range and number of facilities currently available is such that reasonably adequate support can be provided to enable satisfactory flight clearance to be obtained. One area which is not well covered is rotor blade icing, and there are few facilities where scale-model rotors or cropped full-scale rotors can be tested. The proposal to rehabilitate the Altitude Wind Tunnel (AWT) at the NASA Lewis Research Center would partly fill this gap. If this proposal is proceeded with the tunnel will become available for icing work in 1985. NASA are also considering the construction of a small inexpensive icing tunnel for testing two-dimensional aerofoils, instrumentation, etc.

There is a need for an improved inflight simulator (HISS) giving a larger icing cloud, at least 25 x 9 m, and providing for tests of longer duration, for example 20 minutes at an LWC of 3g/m³ and one hour at 1g/m³.

The Ottawa spray rig is a unique facility which enables a full-scale helicopter to be tested in hover conditions with partial immersion in an icing cloud. The utilization of the rig depends on the weather since it relies on natural ambient air temperature and wind speed to provide the test conditions. This, coupled with results which are at variance with those experienced in natural icing, has led some icing teams to reduce their demands on the future use of the rig and this has led to its future availability being placed in jeopardy. However, a significant proportion of the rotorcraft community do find that the Ottawa spray rig provides a useful capability and plans to use it. The Working Group believes that the rig or an improved version of it should be retained.

In Europe, icing test facilities are less numerous but they include a reasonably wide variety of types. Adequate facilities exist for tests on engines and inlets, on components and for testing scale-model rotors (although only in the winter months). However, there is no European equivalent of the HISS tanker and the Working Group considers that the feasibility of operating a HISS-type facility in Europe should be evaluated with a view to possibly recommending the establishment of such a facility for use by European nations.

Another area in which European facilities are deficient is the small icing wind tunnel for instrumentation development and calibration having the desired stability of control of LWC. The RAE in the UK and CEPr in France have given some consideration to the provision of such facilities and the Working Group recommends that these proposals are actively pursued.

Both in North America and in Europe most of the test facilities referred to in this Report are used mainly for work other than helicopter icing. This is particularly true of engine test facilities. It is essential that the critical dependence on the use of such facilities for helicopter development and clearance for operation in icing conditions should be understood by all those responsible for allocating facility usage and priorities. The Working Group wishes to draw attention to this situation and emphasizes its great importance to helicopters.

3.5 SUMMARY OF RECOMMENDATIONS

The Working Group makes the following recommendations with regard to icing facilities for development and clearance testing:

- (a) Some additional icing tunnel facilities should be provided for component, instrumentation, cropped full-scale and possible model rotor testing. These include rehabilitation of the AWT at NASA Lewis, proposed new small tunnels at NASA Lewis, and CEPr Saclay and improvements to the icing tunnel at Lucas Aerospace, Artington. Consideration should be given to retaining or replacing the small high-speed icing tunnel at NRC Ottawa.
- (b) The feasibility of operating a HISS-type facility in Europe should be evaluated with a view to possibly recommending a counterpart for European work. The existing HISS should be developed to provide a larger icing cloud (at least 25 x 9 m) and providing for tests of longer duration, for example 20 minutes at a LWC of 3 g/m³ and 1 hour at 1 g/m³.
- (c) Past work by NRC on the simulation of snow should be reviewed and an evaluation made of the feasibility of producing "technically acceptable" snow for testing engine inlets.
- (d) The results of tests in simulated icing conditions should be compared with those obtained in natural icing so that test facilities can either be validated or the necessary techniques developed to enable extrapolation to natural conditions to be made. In particular the need for a facility to simulate ice crystals should be studied and, if a need is established, methods for producing them investigated.
- (e) The attention of all those responsible for allocating test facility usage and priorities should be drawn to the critical importance of making the facilities available for helicopter icing development and clearance tests.

4. ICE PROTECTION SYSTEM TECHNOLOGY

This section includes discussions of the various helicopter components that require ice protection and the technology for providing protection. Primary emphasis is placed on protection of rotor blades, since fixed-wing aircraft technology, in general, supports the protection of other helicopter components. The helicopter rotor blade, by far, presents the biggest challenge to obtain an efficient, light weight, low cost, and reliable means of ice protection. Today, only three helicopters in the free world are known to have operational clearance with rotor blade ice protection equipment installed. These include the United States (U.S.) Navy CH-46, the Canadian CH-124, and the Aerospatiale SA-330 (PUMA). Many other helicopters have been equipped with rotor ice protection for research or development purposes, and several are currently undergoing qualification or certification tests. All of these helicopters are, or were, equipped with cyclic-electrothermal rotor ice protection, with the exception of one. In 1960 the Bell Helicopter Company (now known as Bell Helicopter Textron (BHT)) performed limited testing of a UH-1 helicopter equipped with a freezing point depressant anti-icing system (ref 4-1). In more recent years, several other concepts of rotor ice protection have been examined for feasibility of application and development. The status of each of these concepts is summarized in this section. Of the three helicopters mentioned above that have or have had operational clearances with rotor ice protection systems installed, only the SA-330, the most recently certified in France, has been cleared for unlimited operation in known or forecast icing conditions. The CH-46 release was withdrawn and the systems deactivated because of excessive system maintenance cost and poor reliability. The CH-124 rotor ice protection system is currently used only as an emergency capability and is not normally used to provide an all-weather operational capability.

4.1 ELECTROTHERMAL ROTOR BLADE ICE PROTECTION

4.1.1 Comparison of System Parameters for Electrothermal Systems

Table 4-1 provides a listing of various helicopters that are being equipped with electrothermal rotor ice protection systems. The aircraft designation, aircraft manufacturer, primary users, and pertinent aircraft characteristics are listed along with various rotor ice protection design parameters for ready comparison. The following key points are noteworthy:

- a. The vast majority of the systems are experimental (for research purposes) or developmental. Only three are considered operational.
- b. With the exception of the U.S. Army's experimental UH-1H and the BHT model 412, all helicopters employ spanwise heating element installations, incorporating several chordwise segments that are heated sequentially. The UH-1H and BHT model 412 helicopters employ the chordwise heating for spanwise shedding concepts. These concepts and their advantages and disadvantages (relative merits) are described in reference 4-2.
- c. Attempts were made to compile system cost data, however, these data were found too difficult to obtain with any degree of confidence and are not included.

Table 4-2 provides a compilation of available ice protection system weight data for comparison purposes. Specific component weights are not available in some instances. In these instances, the total ice protection system is considered an estimate and is so designated by a "+" sign to signify that an additional unknown weight should be added. These data, therefore, should only be used for weight trending purposes.

4.1.2 Icing Test Conditions

Various helicopters that have been equipped with ice protection systems have been designed to various requirements. (Design criteria and disparities existing are discussed in section 1.4). (Operational capabilities of various helicopters cleared for flight in icing conditions are discussed in section 4.6). The purpose of this section is to present available data on the test conditions to which various helicopters have been exposed to date, to reflect available reliability and maintainability data or design goals, and to address helicopter performance degradation experienced or anticipated during flight in icing conditions.

Test conditions encountered to date by various helicopters are given in figures 4-1 through 4-13. Where available, the duration in the test condition is indicated on each figure.

4.1.3 System Reliability and Maintainability

For purposes of this report, attempts were made to assemble reliability and maintainability (R&M) data on various electrothermal ice protection system designs. It was found that accurate R&M data are not readily available. This is suspected to be the case because most of these systems are in the experimental or developmental phases and very little operational experience has been gained to date. The CH-46 helicopter ice protection system is reported to have been deactivated because of a combination of factors; i.e., poor system reliability and high maintenance cost, in addition to the fact that the CH-46 helicopter was being used predominantly in Southeast Asia during the time of the deactivation, and this is not conducive to icing conditions. Further discussion may be found in ref 4-3. Reliability and maintainability are important considerations in the design and development of ice protection systems and estimates of R&M have been made during research-oriented trade-off analyses. Results of one such study are included in ref 4-4. The consensus of the aviation community and results of available studies indicate that reliability of ice protection systems must be at the same level or better than that of the

TABLE 4-1. COMPARISON - MAIN ROTOR ICE PROTECTION - ELECTROTHERMAL

Aircraft	John 18	UH-60A	Tab-44	CH-47D	HC-105	CH-34	Wesker 5	Puma (SA330)	MC-24	SE-214C	YOH-61	CH-46E	YAH-64	412	234	TAHUS
Manufacturer	West	Siemens	Boeing	Boeing	Boeing Vertol	Boeing	Siemens	Siemens	Siemens	Siemens	Siemens	Boeing Vertol	Hughes	Boeing Vertol	Boeing Vertol	Boeing Vertol
User	U.S. Army (2)	U.S. Army (2)	U.S. Army (2)	U.S. Army (2)	U.S. Army (2)	U.S. Army (2)	Canada (2)	Canada (2)	U.K. (2)	U.K. (2)	U.S. Army (2)	U.S. Army (2)	U.S. Army (2)	U.S. Army (2)	U.S. Army (2)	U.S. Army (2)
Gross Weight (lb)	4,560,92	9,185,4	4,560,0	22,00	2,994,8	5,932,4	6,123,6	7,000,4	N/A	9,925,6	8,692,3	10,585,9	6,239,7	5,941,8	21,999,6	35,941
Rotor Blade Number & Type	2 b1	4 b1	3 b1	4 b1	5 b1	4 b1	5 b1	6 b1	N/A	5 b1	4 b1	4 b1	3 b1	4 b1	3 b1	3 b1
Rotor Radius (ft)	132	177	132	134	141	134	141	141	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Percent Rotor Protection	100%	20-93%	93%	26-100%	26-89-93%	20-100%	17-93%	N/A	N/A	N/A	N/A	N/A	19.3-93.2%	N/A	22-99%	Partial
Chord (ft)	.53	.53	.53	.51	.58	.58	.46	.41	N/A	N/A	N/A	.66	.53	.42	.53	.41
Upper	122	122	122	122	132	132	6.52	122	N/A	N/A	N/A	122	82	112	112	252
Lower	298	174	274	234	254	13.82	152	202	N/A	N/A	N/A	232	122	232	232	252
Power Density	1.674.0	1.674.0	1.674.0	4.3	1.674.0	3.6	1.674.7	2.172.7/3.2	N/A	N/A	N/A	4.3	3.9	4.2	4.3	N/A
Heat Loss	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Heater Element	B.P. Gaskets	GoodYear Novex	Siemens	Etched Foil	Spreadmat	GoodYear	GoodYear	GoodYear	N/A	N/A	N/A	GoodYear	Etched Foil	Siemens	Foil	Etched Foil
Element	Foil	Foil	Foil	Foil	Woven	Spreadmat	Woven	Spreadmat	N/A	N/A	N/A	Selected	On Woven Wire	On Woven Wire	N/A	N/A
Protection Shield	STA-C-43 A1 STA-B-1885	Ti/Ti-81 Out. Rd.	Ti-0-707 Ti-70-100%	Steel	W/55	Polyurethane/Ni 67/1002	Ti	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
On-Time/Zone Range	6.5 sec 0-20° C	13 sec 0-20° C	7-8 sec 0-20° C	15 sec 0-20° C	16 sec 0-15° C	2 sec & 0° C 20 sec & -18° C	5 sec & -10° C -10° C & 10° C	Fixed 10 sec 0 to -30° C & 15 sec	N/A	N/A	N/A	11.25 sec 0-25° C	1.2 sec @ -20° C 1 sec @ -30° C	1.2 sec @ -20° C 4.3 sec @ -30° C	1.2 sec @ -20° C 4.3 sec @ -30° C	1.2 sec @ -20° C 4.3 sec @ -30° C
Type	C	S	S	S	S	S	S	S	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Zone Number	6	4	5 or 6	6	6	4	5	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Elect. System	36,400 Hz 250 V a.c.	36,400 Hz 250 V a.c.	268 V d.c. A, N	268 V d.c. A, N	268 V d.c. A, N	268 V d.c. A, N	268 V d.c. A, N	268 V d.c. A, N	N/A	N/A	N/A	N/A	115 V a.c. 450 Hz 250 V d.c.	115 V a.c. 450 Hz 250 V d.c.	115 V a.c. 450 Hz 250 V d.c.	115 V a.c. 450 Hz 250 V d.c.
Control Type	A, S, N	A, N	A, N	A, N	A, N	A, N	A, N	A, N	N/A	N/A	N/A	N/A	A, N	A, S, A	A, S, A	A, S, A
Loss (W)	1.0	1.0	0.5	1.0	N. O. D	0.8	N. O. D	N. O. D	N/A	N/A	N/A	N/A	1.5	0.5	0.5-1.0	1.0
Do w	50	20	N/A	10	N/A	20	N/A	N/A	N/A	N/A	N/A	N/A	30	25	25	25
Do Tc	-20	-20	-18	-18	-18	-20	-20	-20	N/A	N/A	N/A	N/A	-18° C	-20° C	-22° F	-18° C
Total Sve	250.6	34.0	46.0	46.0	54.0	54.0	71.7	N/A	N/A	N/A	N/A	N/A	51.7	N/A	N/A	N/A

UNCD

X - Experimental
D - Developmental
O - Operational
C - Clearance Shading
S - Spurious Shading
A - Automatic
S.A. - Semi-Auto
N - Manual
N/A - Not Available

TABLE 4-2. ICE PROTECTION SYSTEM WEIGHT (kg)

	<u>TAURUS</u>	<u>CH-47D</u>	<u>JUH-1H</u>	<u>YUH-60</u>	<u>UH-60A</u>	<u>YUH-61</u>	<u>YAH-64</u>	<u>CH-124</u>	<u>WESSEX 5</u>	<u>BO-105</u>	<u>SA-330</u>
Main Rotor Blankets	18	0	18.1	5.1	4.5	0	2.9	0	0	2.7	6.0
Main Rotor Slip Rings	--	13.6	4.5	2.3	5.0	3.7	2.3	4.1	9.5	2.5	10.0
Tail Rotor Blankets	--	--	1.4	.5	2.7	0	.3	2.5	1.5	.3	3.2
Tail Rotor Slip Rings	--	--	3.2	1.8	1.8	1.7	2.5	1.4	N/A	1.7	6.5
Controller/Distributor	--	4.3	6.8	5.0	5.0	9.5	10.9	6.5	11.7	7.2	12.6
Cockpit Controls & Displays	--	N/A	2.3	1.4	1.4	.5	.2	1.4	N/A	.6	2.6
Ice Detector	2.0	1.6	2.3	1.8	1.8	.8	.2	N/A	2.3	5.0	N/A
Windshields & Controls	15.0	4.9	16.8	N/A	0	N/A	N/A	N/A	N/A	6.2	N/A
Generator & Controls	57.0	0	-7.7	0	0	2.8	12.7	N/A	15.4	25.0	36.6
Wiring, Relays, Etc.	--	86.6	70	19.5	25.0	34.3	17.0	47.5	16.0	13.2	28.7
Engine Inlet	34.6	--	31.8	8.8	11.3	15.6	7.7	21.5	7.3	6.0	13
Other	15.4			?	23.0	?	3.4	?	?	--	?
					10.4	1.5			10.0	5.3	
									4.5	2.4	
Reduction (Main & Tail Rotor Blades)									-63		
Total	92.0	79.1+	78	26.8+	44.0	34.7+	41.2+	41.9+	50.0+	54.3	90.5+
									-28.6		

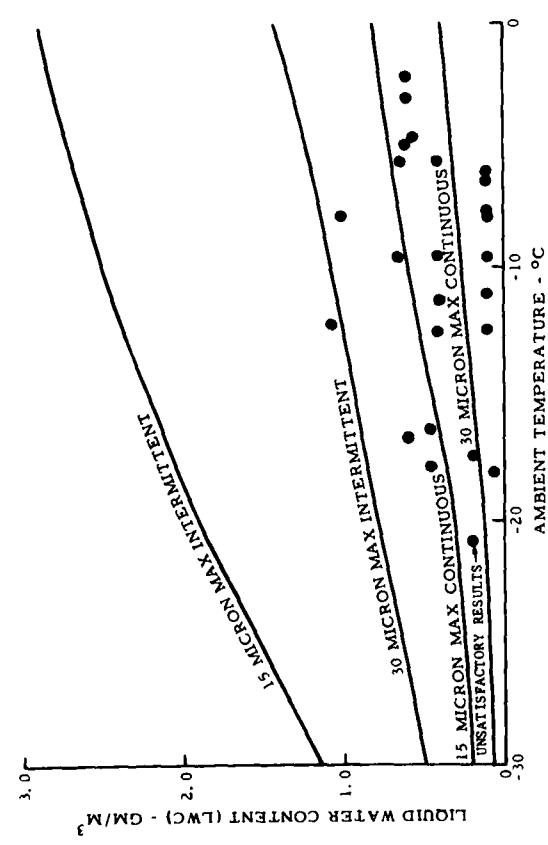


FIGURE 4-1. CH-124 TEST POINTS, OTTAWA SPRAY RIG - 1970

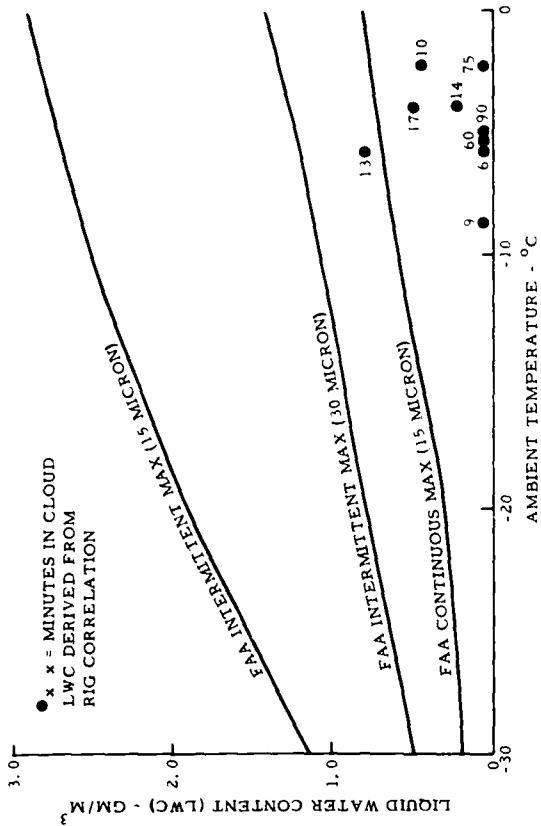


FIGURE 4-2. CH-124 TEST POINTS, NATURAL ICING - 1970

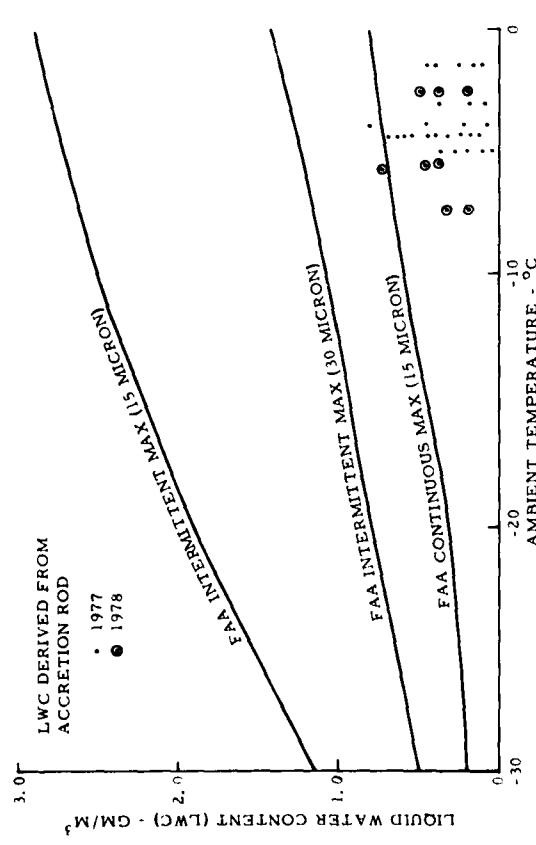


FIGURE 4-3. PUMA TEST POINTS, CONTINUOUS MAXIMUM ICING CONDITIONS

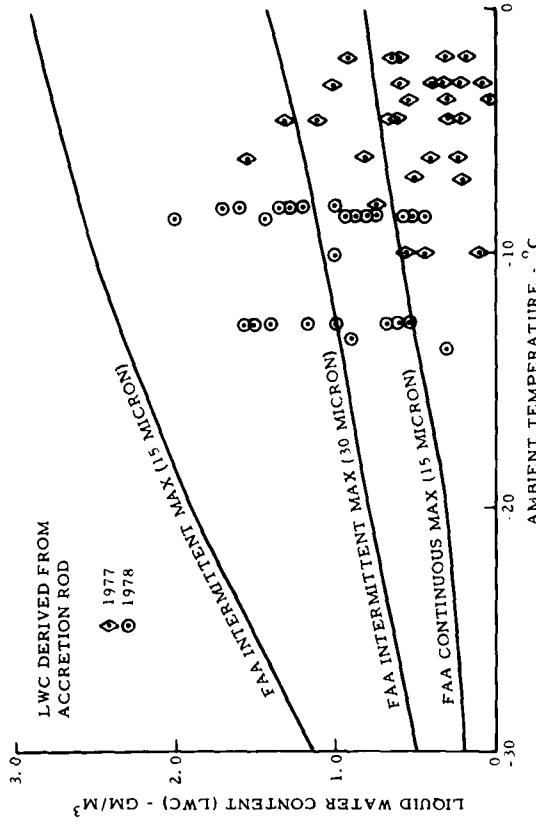


FIGURE 4-4. PUMA TEST POINTS, INTERMITTENT MAXIMUM ICING CONDITIONS

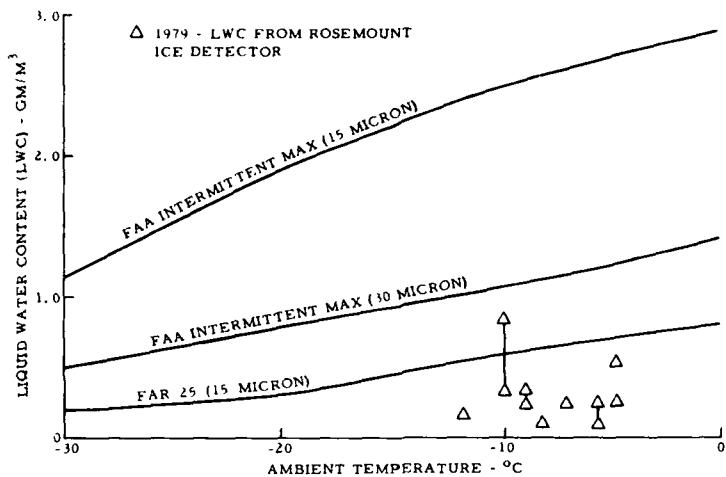


FIGURE 4-5. YCH-47D, NATURAL ICING TEST POINTS - 1979

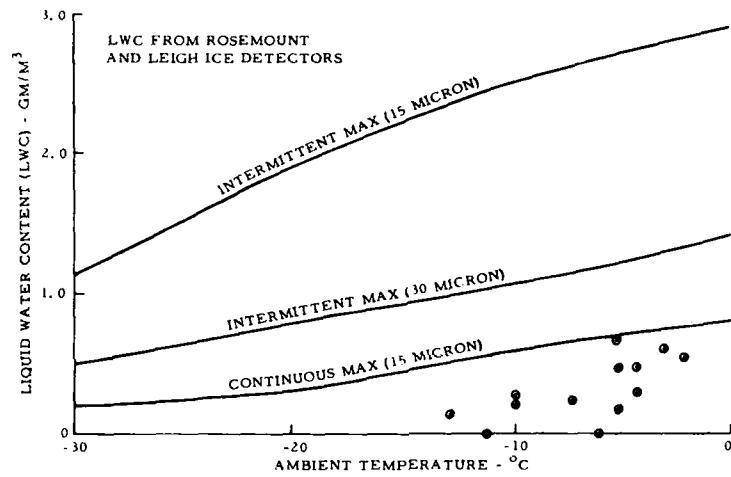


FIGURE 4-6. YCH-47D, NATURAL ICING TEST POINTS - 1980

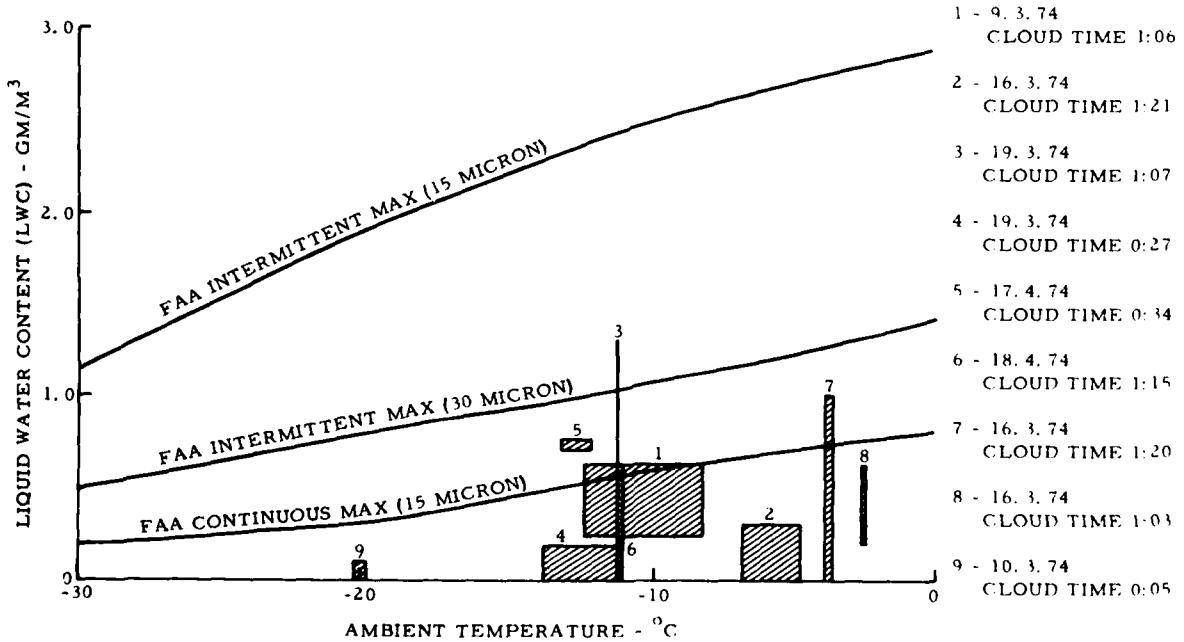


FIGURE 4-7. BO-105, NATURAL ICING TEST CONDITIONS - 1974

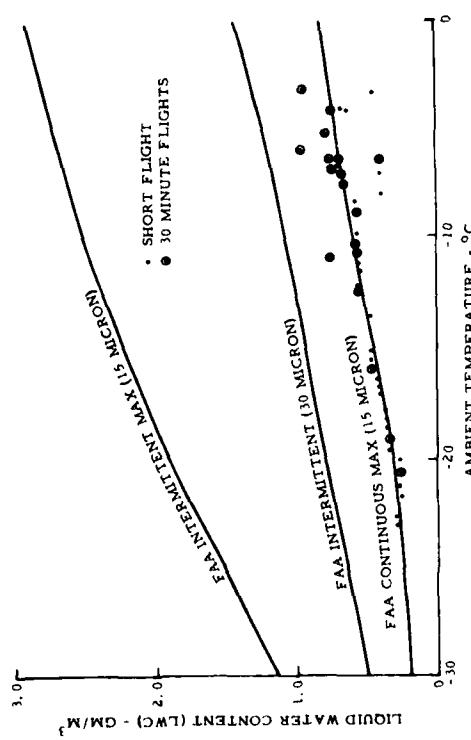


FIGURE 4-8. BO-105 TEST POINTS, OTTAWA SPRAY RIG

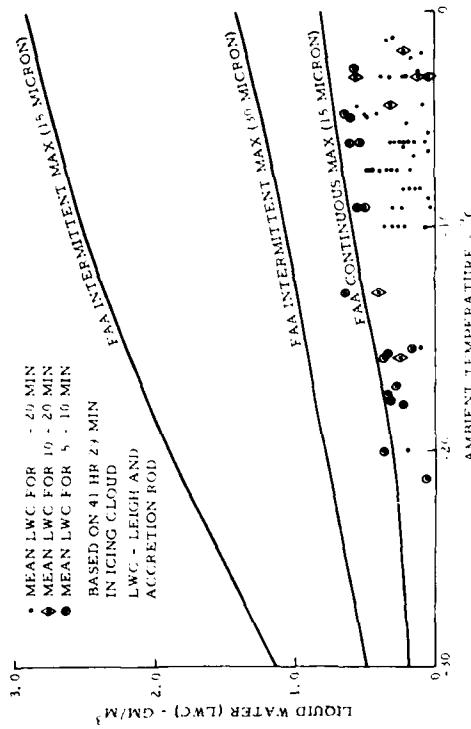


FIGURE 4-9. WESSEX 5 NATURAL ICING TEST POINTS

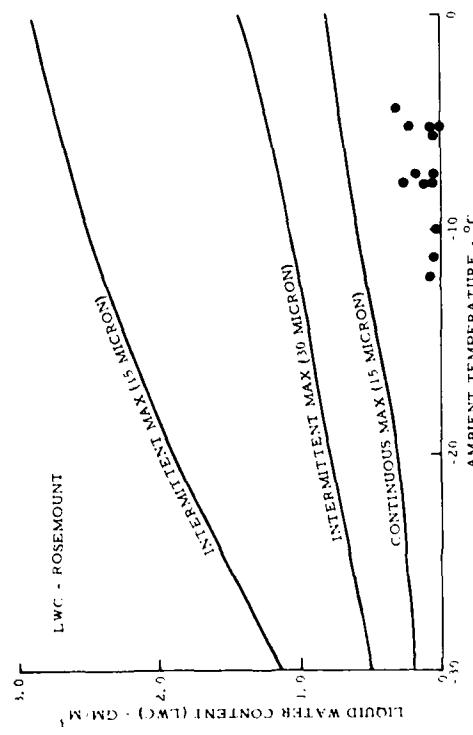


FIGURE 4-10. UH-60A (BLACKHAWK) NATURAL ICING TEST POINTS - 1980

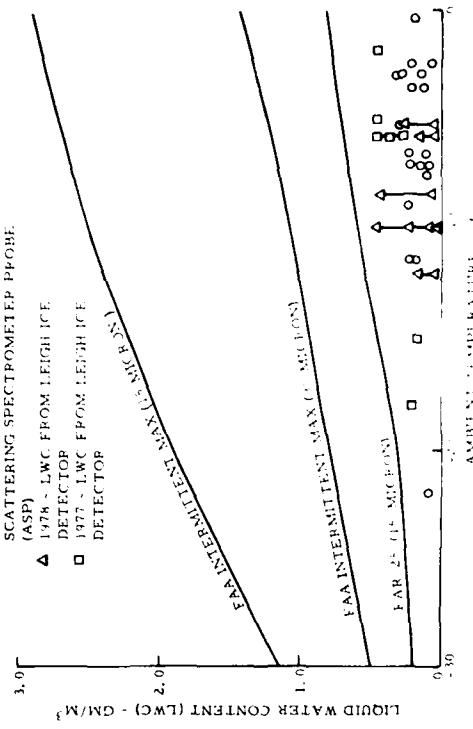
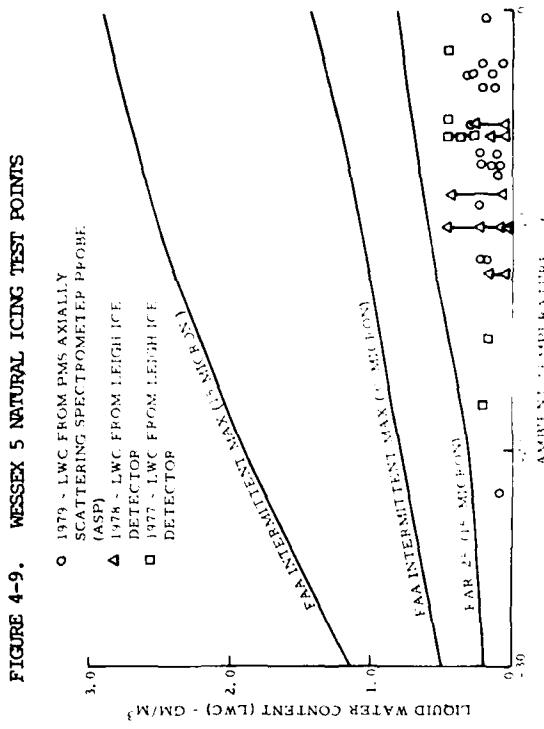


FIGURE 4-11. JUH-1H NATURAL ICING TEST POINTS



Flight-Test Summary (Time Expressed in Hours)							
Flight-Test Period	Total Miss	Miss Cloud	Total OSR	OSR Cloud	Total Natural	Natural Ice	Other Product
							Snow FR Rain
12 - 31 Mar 1975 (19 Days)	16.8	2.7					
21 Jan - 16 Mar 1976 (55 Days)			48.1	7.3			0.5
17 Feb - 15 Apr 1977 (57 Days)			13.1	3.4	17.3	6.5	
31 Jan - 31 Mar 1978 (60 Days)			8.8	4.4	15.2	6.7	0.8 1.0
22 Jan - 23 Mar 1979 (60 Days)	16.6	7.2			18.0	9.9	0.8
TOTALS	33.4	9.9	40.0	15.1	50.5	23.1	2.1 1.0
Total Cloud (251 Days) - Simulated Natural			25.0	'3.1			

FIGURE 4-12. JUH-1H FLIGHT TEST SUMMARY

Flight Test Period Day, Month, Year	Flight Test Time (Hours)					
	Total Ottawa Spray Rig	Ottawa Spray Rig Cloud	Total Natural	Natural Ice	Other Product	
					Snow	Fr Rain
18.02.72 ~ 10.03.72	14,5	3,6				0,3
15.12.73 ~ 24.01.74			24,5	4,5		
02.02.74 ~ 19.03.74	27,2	23,4	7,0	6,5	0,6	0,3
09.04.74 ~ 18.04.74			5,8	1,8		
09.01.77 ~ 13.03.80			8,7	7,8	2,0	

Company Flight Tests

Test Center of German Army

80-208-4-13

FIGURE 4-13. BO-105 FLIGHT TEST SUMMARY

basic aircraft or its systems and that, as a design goal, the ice protection system should not increase the maintenance burden by more than four maintenance man hours per 1,000 flight hours. Results of studies conducted to date indicate that existing technology can support these goals with proper design implementation.

4.1.4 Performance Considerations

For purposes of this report, attempts were made to assimilate data that would quantify performance degradations experienced by various helicopters during flight in icing conditions. It was found that, although significant flight test data exists, very little effort has been expended in assessing that data to the extent necessary to quantify the performance penalty.

The most significant aspect of understanding the performance penalty is the reduction in range and endurance that could be induced by several factors during flight operations in icing conditions. These factors include: increased power and fuel consumption associated with ice formation on the rotor blade between deicing cycles, power demands during the deicing cycle, residual ice on protected and unprotected surfaces as well as power losses imposed by engine bleed air extraction and by ice formations on engine inlets and barrier screens.

A typical example of the effects of ice formations on rotor blades between deicing cycles is illustrated in figure 4-14 where torque rise and fall is shown as a function of time in natural icing conditions.

The only known assessment of performance degradations was made by the U.S. Army Applied Technology Laboratory (ATL) and the results reported in reference 4-4. These assessments were made using limited performance data obtained during U.S. Army research testing and can only be used for approximation purposes.

It is apparent that more attention is needed to the acquisition of performance related data during experimental, developmental, qualification, or certification flight test programs so that performance degradation can be quantified, understood, and minimized.

4.1.5 Environmental Tolerance

Electrothermal rotor ice protection systems can be broken down into three subsystems:

- heating mats,
- slip-ring distributor unit, and
- control and indication electronics.

These subsystems are exposed to weather conditions that may cause deterioration or a reduction in service life.

With regard to the slip ring and the electronic units, the weather conditions they are exposed to are well established. There are standards indicating the conditions in which systems must be tested for qualification (e.g., the French standard AIR 7304 and MIL-STD-210 B), with the exception of electric and radio-electric phenomena.

There is no reason to believe that these ice protecting systems are different in nature to other items of equipment. Therefore, they require no special development.

The following paragraphs consider the resistance of heating mats to erosion, impacts, vibration, and electrical phenomena (lightning, and the resistance of the electronic systems to lightning strikes and static discharge.

To understand how heating mats become eroded, it should be remembered that they consist of electrical resistor elements enclosed in an insulating layer generally made of polyurethane, but which may, as in the case of UH-1H, be a composite material (glass fibers coated with resin).

A. Erosion

Rain. Both polyurethane and resin-coated glass-fiber are highly vulnerable to moisture. The incubation time of polyurethane is about 10 times less than that of metals.

In view of the intended use of helicopters equipped with ice protection, it is essential that heating mats be protected against rainwater (moisture) corrosion. A highly effective method is to provide the whole heating mat with a metal shield that is properly sealed to eliminate any possibility of water ingress. Figure 4-15 presents the relative life of polyurethane and ultra high molecular weight polyethelene (UHMWPE) erosion shields in rain and sand environments.

Sand. Although less resistant to rain erosion, polyurethane has much better resistance to sand than metals.

The erosion rate of polyurethane is approximately four times slower than that of the metals used for leading edge protection (stainless steel and titanium) in the sand and dust environment.

It is therefore necessary to make a choice: whether to leave the heating mats

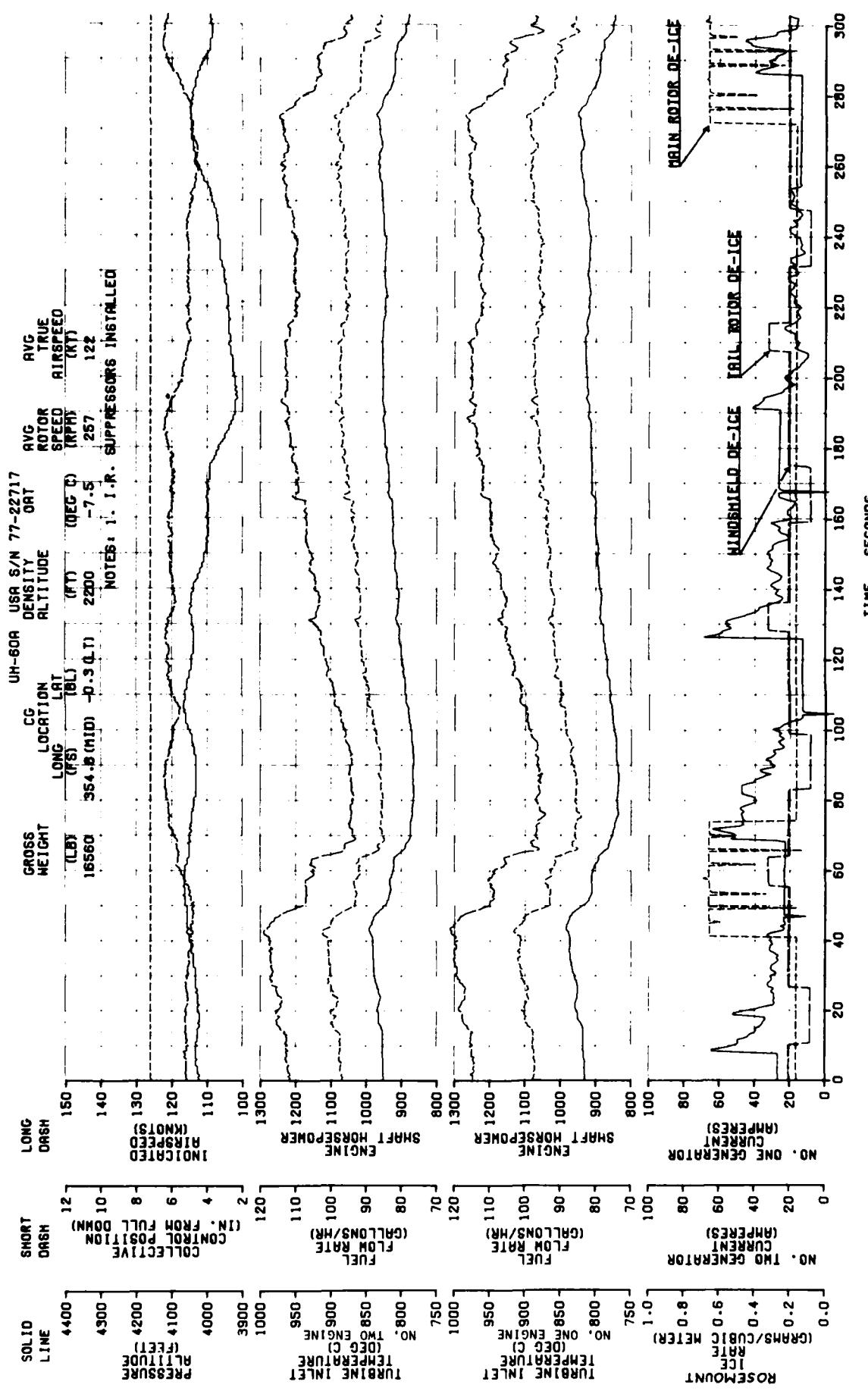


FIGURE 4-14. BLADE DEICE CYCLE TIME HISTORY

unprotected and accept rain erosion, or to protect the mat from the rain and suffer sand erosion. This is not satisfactory. The objective should be to have heating mats fully protected against rain and sand erosion.

It is clear that the problem of rain or sand erosion of leading edges is not limited to aircraft fitted with electrothermal deicing systems, since protection against erosion is required in all cases, whether the blades are metal or composite.

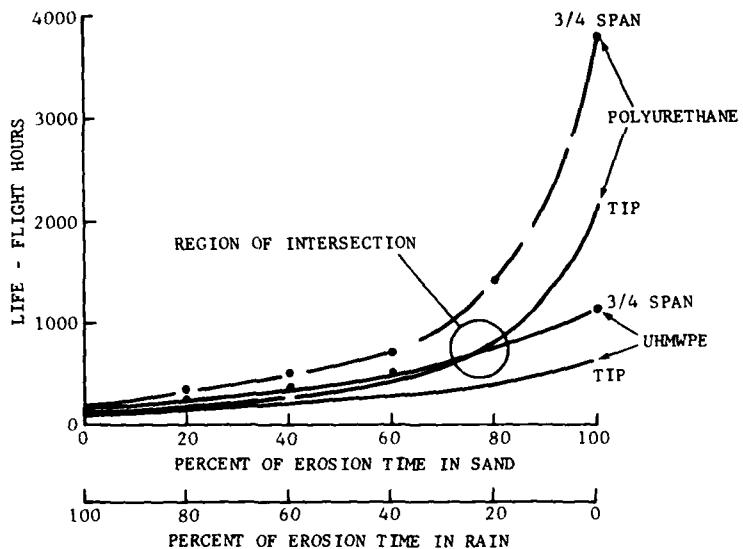


FIGURE 4-15. RELATIVE LIFE OF EROSION SHIELD MATERIALS

B. Impact (Hailstones)

No manufacturer has reported any incident in which the heating mats were damaged by hail when protected by a metal erosion shield. The resistance of heating elements to impact from hailstones or ice particles coming loose from the fuselage does not seem to have been questioned.

There are documented cases of hailstone impact testing on PUMA blades (reference 4-5) which showed that hailstone impact leaves no trace on the rotor blade leading edge.

C. Vibration

Rotor blades are subjected to considerable distortion in use. Since the heating mats are integral with the blade, they must be strong enough to resist the effects of vibration. The problems areas are:

- (a) bonding of the heating mat to the blade, and
- (b) fatigue strength of the heating elements.

The problems of bonding these or other items to the leading edge of rotor blades have been overcome nowadays.

The necessary mechanical strength of heating elements can be ensured by appropriate design and fatigue testing.

Conduct of fatigue testing (mechanical loading and thermal shock) on blades equipped with heating mats should suffice for the detection of any weak points.

The service life of the heating mats should be the same as for the rotor blades.

D. Lightning Strikes

The extension of a helicopter's flight envelope to icing conditions implies a probability of the aircraft being struck by lightning. Although this probability is less than for aeroplanes, it should be reckoned that an IFR helicopter providing regular service will be struck by lightning every 1,500 or 2,000 hours in flight. Few cases of lightning striking a helicopter in flight have been reported to date, and none has endangered the aircraft's safety.

With respect to heating mats, the voltage strike tests carried out at the request of the French authorities showed that the strike areas on rotor blades are the blade tips and trim tabs. The leading edge does not seem to be a strike-prone area, being completely smooth.

Evidently, if the metal shield over the heating mats were struck by lightning it might be pierced and the heating mat damaged.

In any case, the electric arc travels through the blade periphery if the blades are made of metal or carbon. Electrical bonding must be provided between the blade and the airframe.

The electronic systems must be protected against overvoltage. The design of heating mat electronic indication and control systems must include:

- (a) completely screened circuits,
- (b) clipping of voltage peaks, and
- (c) voltage-resistant components.

The lightning resistance of electronic systems, as a whole, should be demonstrated by lightning strike simulation tests on an actual aircraft.

4.2 ICE PHOBIC COATINGS

The materials which will be considered in this section can be broadly categorized as follows:

Material	Physical Characteristics	Examples
State		
Fluid	miscible with water	glycols, alcohols, etc
	not miscible with water	oil
Paste	containing FP depressants	--
	not containing FP depressants	greases
Solid	low surface energy coatings	PTFE

Work aimed at assessing the suitability of ice phobic coatings for application to helicopter rotor blades has been in progress for some time, both in the United Kingdom and in the U.S.

In the U.K. several pastes have been tested in the Lucas Aerospace icing tunnel at Artington using a full-scale section of Wessex rotor blade. Limited flight trials have also been made at the Royal Aircraft Establishment (RAE), Bedford on a PUMA helicopter and on the Sea King. The results are given in reference 4-6 and A&AEE Note 3188, dated August 15, 1977. It was concluded that, whilst a paste made from cheap, readily-available materials would cause ice to shed continuously for up to 1 hour in ice particle free, continuous maximum icing conditions simulated in the wind tunnel, flight trials showed that the paste was rapidly eroded by rain drop and ice particle impact.

Similar limited tests have been made in the U.S. The results are summarized in reference 4-7, which concludes that "ice phobics show promise for application to rotor blades and may provide at least a limited capability for flight in supercooled cloud icing conditions where the LWC is less than 0.5 gm/m^3 and the ambient temperature is no lower than -10° . It is strongly emphasized that ice phobic coatings are not expected to provide ice protection over the full range of meteorological design criteria.

TABLE 4.3
ICE PHOBIC MATERIALS TESTED TO DATE

Manufacturer	Type	Ref. No.	Remarks
GE Silicone Products Div., Waterford, NY	Silicone Grease	G-697	Flight tested on UH-1
Dow Chemical Co.	Cationic	E2360	Flight tested on UH-1H
Midland, Michigan	Silicone Oil		
RAE Farnborough	Paste	113	Flight tested on PUMA

4.3 MICROWAVE DEICING SYSTEM

A schematic of a Microwave Deicing System, installed on a helicopter rotor blade, is shown in figure 4-16. The following is an abbreviated description of its operation, as given in the feasibility study of the Microwave Deicing System funded by the U.S. Army (reference 4-8 and 4-9). A high-power microwave tube converts electrical power to microwaves. The microwaves then travel through a series of waveguide transmission elements (rotor shaft, rotary joint, power divider, and wave launcher) to an array of thin surface waveguides. The thickness of these polyethylene surface waveguides on the blade is about 1/8 inch for the preferred microwave frequency of 22 GHz. Any ice on the blades is heated by the microwaves. When the interface of the ice and waveguide is heated above the de-bond temperature (temperature where the ice bond strength is near zero; close to 0°C), the ice can be pushed off by aerodynamic and "G" forces. In figure 4-16, the microwaves are launched at the blade root or tip, so that ice near the root is heated first; the ice sheds a little at a time, starting at the root and moving outward to the tip of the blade. The microwave deicing system is similar to an electrothermal deicing system, in that both attempt to heat a thin layer at the ice-blade interface instantly to the de-bond temperature (near 0°C) over a large area of the blade. Unfortunately, this minimum energy level is hard to accomplish in practice. In both systems, the blades are deiced piecemeal (a small area at a time) so that the peak power requirement does not exceed the supply.

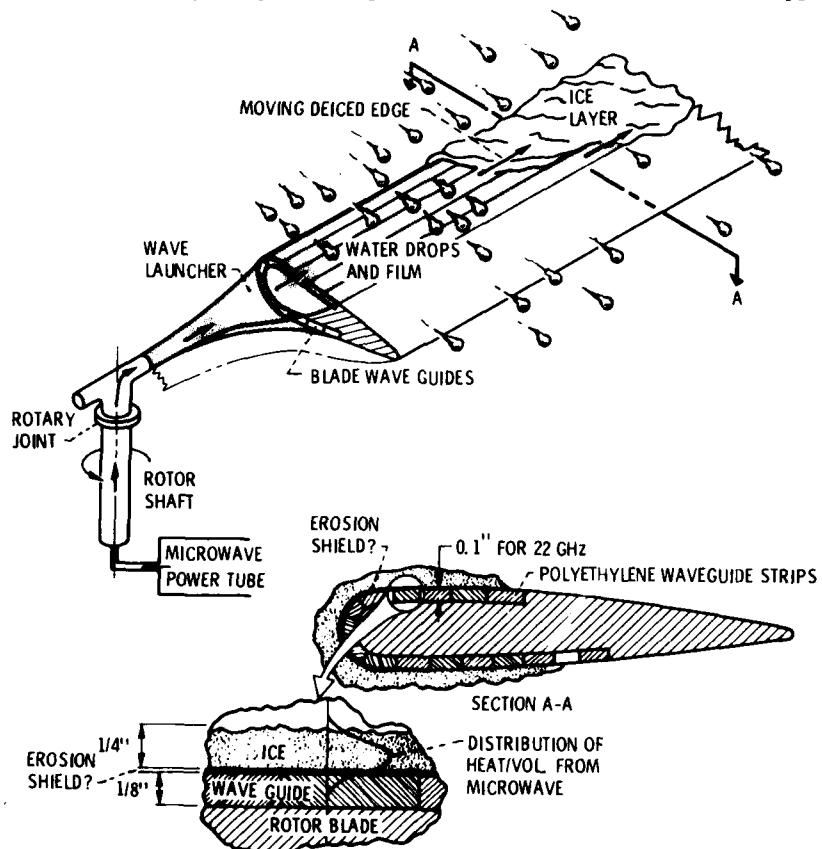


FIGURE 4-16. MICROWAVE DEICING SYSTEM ON ROTOR BLADE

The Microwave Deicing System investigated in references 4-8 and 4-9 is a novel concept that should work in principle. NGTE, NASA, NRC and CRREL made independent preliminary evaluations of this concept. All evaluators were pessimistic (see references 4-10, 4-11, 4-12, and 4-13) about its potential as a replacement for the electrothermal deicing system which is currently used on rotor blades. Many serious problems were pointed out in these preliminary evaluations. Probably the most serious problem was that the electrical and thermal efficiencies are expected to be poor, relative to the electrothermal system.

The evaluation brought out two areas where further research may be useful.

a. NRC suggested that a thin glossy layer on top of the waveguide would probably be the best way to configure a microwave deicer so that it could favorably compete with the electrothermal deicer.

b. A computer program is urgently needed that can accurately calculate the heat required by the microwave and electrothermal deicing systems for proper ice shed. This

complex program must include three dimensional transient heat conduction in a multi-layer solid, heat transfer to the cold air/droplet environment, moving phase boundaries from shedding and melting, and the ice beam structure which breaks and sheds when it is locally debonded from the blade and subject to aerodynamic and "G" forces.

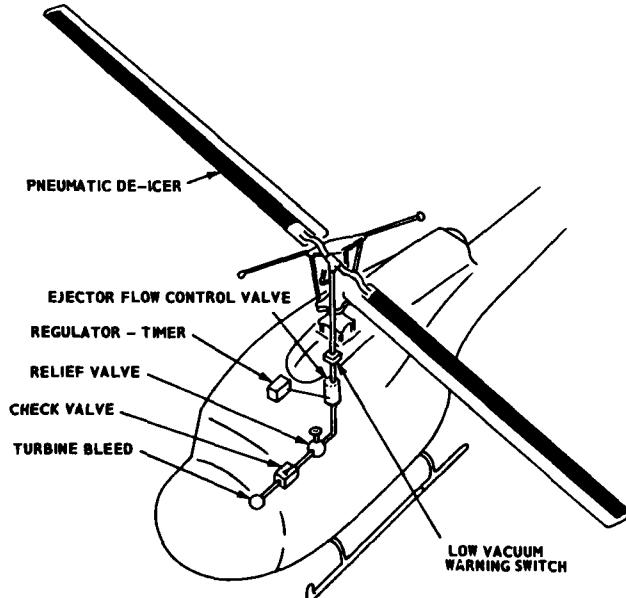
4.4 OTHER ROTOR BLADE ICE PROTECTION CONCEPTS

4.4.1 Pneumatic Boot for Helicopter Rotor Deicing, Status Report

The pneumatic boot concept for rotor blade ice protection was assessed in 1973 by the Lockheed-California Company and rejected (reference 4-14). Several reasons were listed by Lockheed for rejecting the pneumatic boot concept (reference 4-4) but the most significant concerns centered around materials technology. A primary question was raised as to whether the pneumatic boot, constructed of currently available materials, could withstand the severe dynamic environment of the helicopter rotor blade. Specific concern was expressed that the boots may be damaged or completely torn off by the centrifugal force environment.

Further questions were raised concerning erosion (due to sand and dust or rain) and also the possible adverse aerodynamic effects of the inflated tubes on the small, thin airfoils of a rotor blade. Since then, the B.F. Goodrich Company has further developed/improved materials and techniques of pneumatic boot manufacture and has conducted limited testing. Details of the B. F. Goodrich efforts are proprietary; however, a recently proposed B.F. Goodrich concept for rotor blade deicers which incorporates a polyurethane elastomeric material, rather than the old technology neoprene, indicates that it may be feasible to develop lightweight, cost-effective boots for rotor blade ice protection. B. F. Goodrich claims that this polymer can be compounded to exhibit many superior properties such as erosion (rain and sand) resistance (5 to 10 times greater than neoprene), field repairability, greater compatibility to ester oils, and higher strengths and fatigue resistance. High centrifugal loads also presented no indicated distortion problems during tests conducted by B.F. Goodrich to date.

A schematic diagram of the pneumatic system applied to a UH-1H helicopter is shown in figure 4-17 (reference 4-14). Also, as stated in reference 4-14, B.F. Goodrich estimates that this system would weigh approximately 30 pounds (13.6 kg) (43 percent of the estimated electrothermal system weight), could be applied to existing rotor blades and that cost would be much less than for the proposed electrothermal concept.

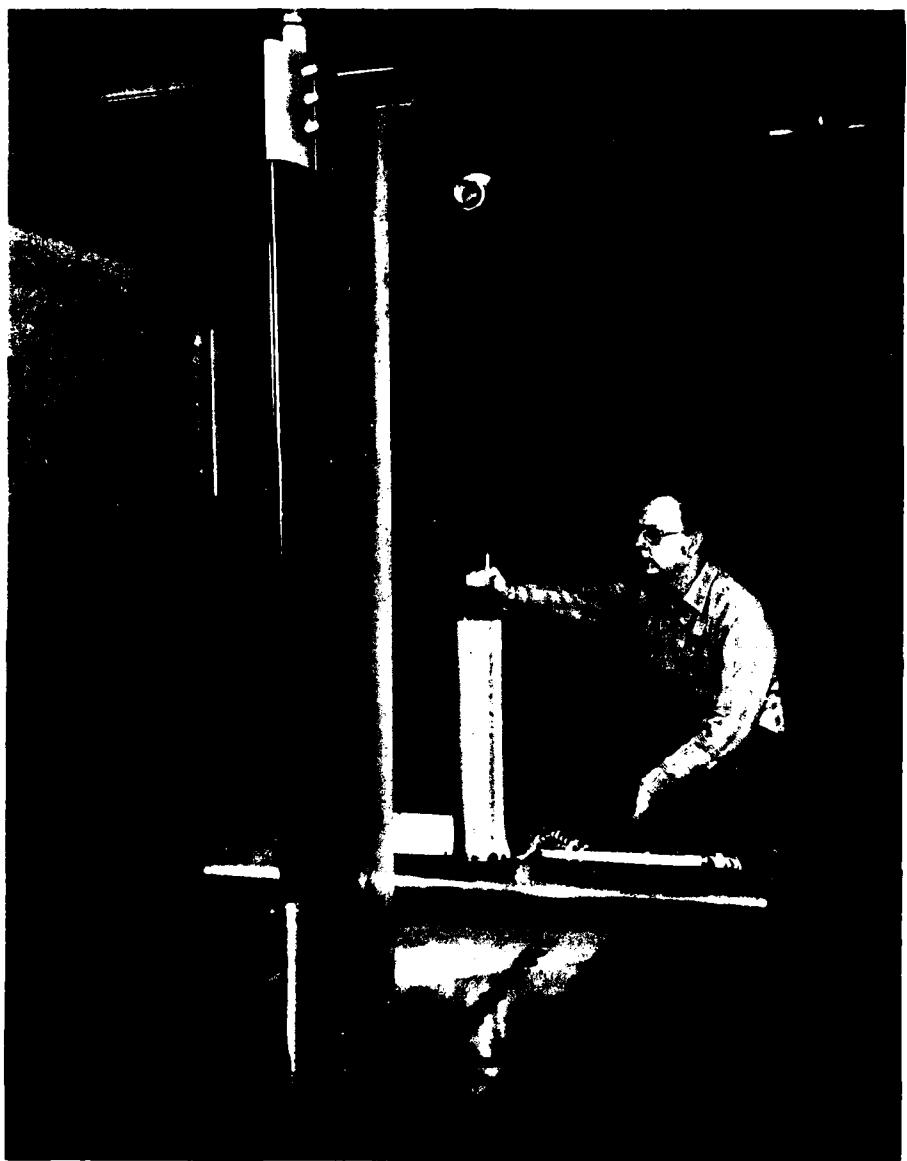


80-208-4-17

FIGURE 4-17. MAIN ROTOR APPLICATION, MECHANICAL-PNEUMATIC DEICER

In an initial attempt to further evaluate the boot concept for rotor blades, ice protection tests were conducted in 1979 in the NASA Lewis 6 by 9 foot (1.8 by 2.7 meter) Icing Research Tunnel (IRT) on a 6-foot (1.8 meters) long segment of a UH-1H rotor blade. In these tests, several boot configurations were evaluated by bonding them on the leading edge of an actual blade segment causing slight airfoil discontinuities. These boots included combinations of spanwise and chordwise tubes, as illustrated in figure 4-18. The test blade section was held stationary during tests, therefore neither the rotating or bending loads were simulated. Also the high rotor tip speeds could not be simulated, since the tunnel capability is limited to 134 meters/second (m/sec). Angle-of-attack was varied from 0° to 16° (stall) without ice and from 0° to 10° with ice. Cyclic motion of the blade was simulated by icing the model at one angle-of-attack and deicing the model at another. With the best boot configuration, a series of model drag measurements were made with a translating wake survey probe also shown in figure 4-18.

NASA
C-79-1686



80-208-4-18

FIGURE 4-18. PNEUMATIC BOOT ROTOR MODEL INSTALLED IN 6X9 FOOT IRT

The results of these tests were very encouraging, and as shown in figure 4-19 the pneumatic boot proved to be fairly effective at deicing the blade. In each test, approximately 1 cm of ice was allowed to accrete before the boot was activated. The drag penalties associated with the ice ranged from 150 percent to values greater than 300 percent when stall was incurred. With the ice present, the stall angle-of-attack was reduced from 16° to approximately 9.5° . When the boot was activated to deice the blade, the residual drag measured ranged from 3 to 55 percent, much less than seen with the ice.

AIRFOIL: NACA 0012

$$V = 250 \text{ MPH}; \alpha = 5.4^\circ; T_f = 21^\circ\text{F}$$

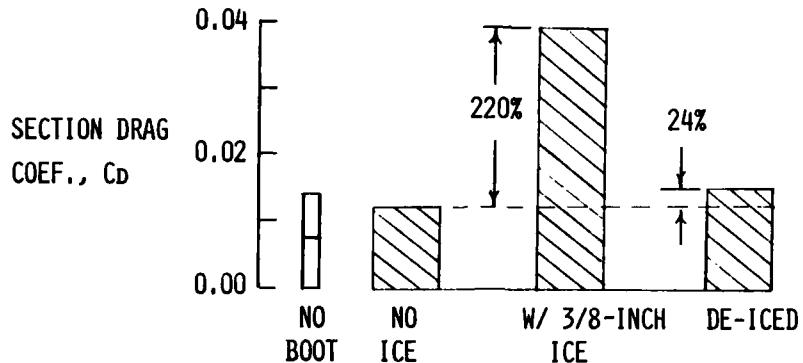


FIGURE 4-19. PNEUMATIC BOOT DEICING

Measurements of the section drag coefficient without ice, but with the boots inflated, indicated drag increases of up to 100 percent but still considerably less than the drag incurred with 1 cm of ice. Inflating the boot without ice also reduced the stall angle-of-attack to near 9.5° at an airspeed of 134m/sec. No drag measurements were made on the airfoil without the boot but comparison with old NACA data (reference 4-15) indicate that the penalty of installing these boots on a NACA 0012 blade section was essentially zero. The aerodynamic penalty of the pneumatic boot concept when applied to modern, thinner leading edge airfoils has not been determined.

The above results were considered to be very encouraging and it is felt that the boots will perform better in the dynamic environment, due to increased aerodynamic and centrifugal loads. As a result of these tests, NASA Ames has initiated a program to test the pneumatic boot concept with full-scale rotating hardware. This program, as shown in figure 4-20, will first evaluate the aerodynamic performance and safety of the rotor with the boots installed and then eventually lead to in-flight icing tests. First phase testing (tie down) is scheduled to begin in June 1981.

	80 O N D	81 J F M A M J J A S O N D	82 J F M
INSTALLATION OF BOOT ON UH-1H		▲	
PRE-TEST SAFETY VERIFICATION		TIE DOWN	
FLIGHT TESTS			
(NON-ICING)		—	—
(ICING) OTTAWA		—	▲
MISS		—	—

FIGURE 4-20. PROPOSED SCHEDULE - PNEUMATIC BOOT TESTS

4.4.2 Vibratory Concept

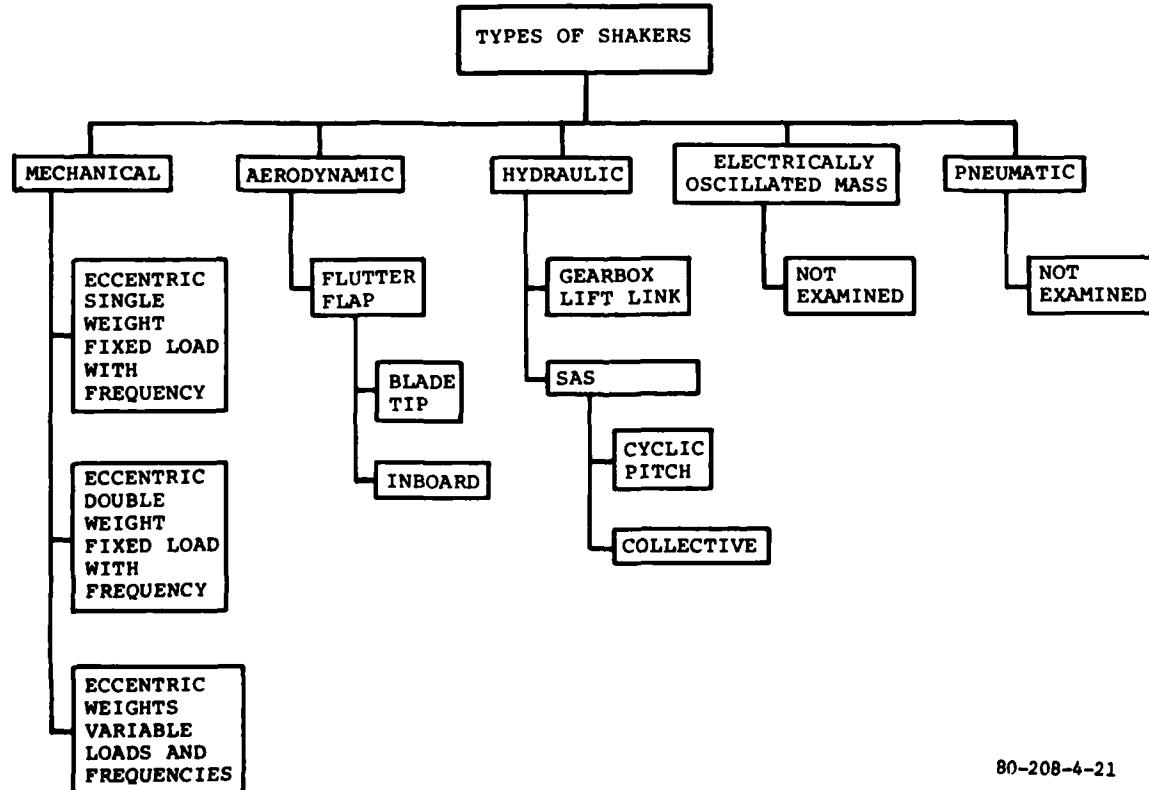
4.4.2.1 Introduction

Various methods of vibrational deicing of main and tail rotor blades were investigated by Bell Helicopter Textron under contract to the U.S. Army Applied Technology Laboratory. Results of this effort are contained in reference 16, USAAMRDL TR77-29, and are summarized herein. Basically, this concept involves exciting the blade through forcing function shakers mounted at various locations on the aircraft. Modal shapes are selected which cause the deicing based on strain of the ice/surface bond (essentially skin strain) and produce the accelerations related to the blade higher harmonic motion. The blade modes selected for excitation of the rotor may be symmetric or asymmetric in nature. The strain on the ice/surface bond, necessary for effective deicing of a metal blade, has been measured in ice chamber tests under an Independent Research and Development (IR&D) program; strain criteria developed from these tests were used to study the effectiveness of vibrational deicing of several helicopters. While the study was limited to beamwise mode excitation for the design effort, chordwise modes were reviewed also for strain effects. Chordwise strains required for deicing were unacceptable. Torsional and coupled modes were not reviewed as computer technology does not encompass valid solutions; no reason exists for believing these modes would not be acceptable for use.

4.4.2.2 Configurations

Modal excitation of rotors for vibrational deicing may be accomplished by many approaches as shown in figure 4-21. This investigation reviewed various means and selected the most promising systems for design evaluation. The aircraft of table 4-4 were reviewed for applicability, and possible blade shaking systems, defined by location, are as follows:

- In the blades (cavity required)
- On the exterior of the blades
- At the hub
- In the controls (fixed or rotating systems)
- On the gearboxes



80-208-4-21

FIGURE 4-21. TYPES OF SHAKERS

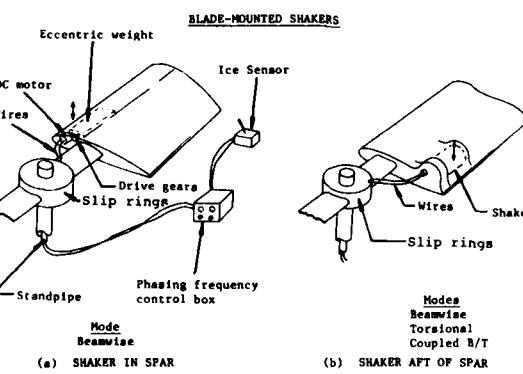
TABLE 4-4. AIRCRAFT APPLICATIONS CHART FOR VIBRATIONAL DEICING SYSTEMS

AIRCRAFT	DEICING SYSTEMS							
	T/R GEARBOX	M/R GEARBOX	BLADE TIP	ON HUB	IN BLADES	BLADE LEADING EDGE	PITCH CHANGE	
UH-1	x	x	xx	x		x	x	x
AH-1	x	x	xx	x		x	x	x
AAH Hughes	x	x	xx	x	-	x	x	
OH-58	x	x	--	x	-	x	x	
UTTAS Sikorsky	x	*	xx	x	*	x	x	
ASH	x	*	xx	x	*	x	x	
CH-47	xxx	*	xx	x	*	x	x	

x Probable
 - Not Possible
 xx Requires Blade Redesign
 xxx Not Applicable
 * Unknown

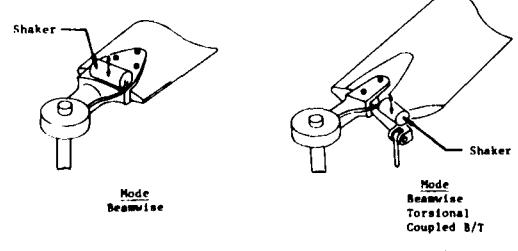
Figure 4-22 shows some schematic approaches to this location selection. Shakers may be of the following types as shown on the morphological chart of figure 4-21.

- Mechanical
- Aerodynamic
- Hydraulic
- Electrical
- Pneumatic



(a) SHAKER IN SPAR (b) SHAKER AFT OF SPAR

BLADE-MOUNTED SHAKERS



(c) SHAKER ON BLADE ROOT (d) SHAKER ON PITCH ARM

80-208-4-22

FIGURE 4-22. EXAMPLES OF SOME POSSIBLE SHAKER MOUNTING LOCATIONS

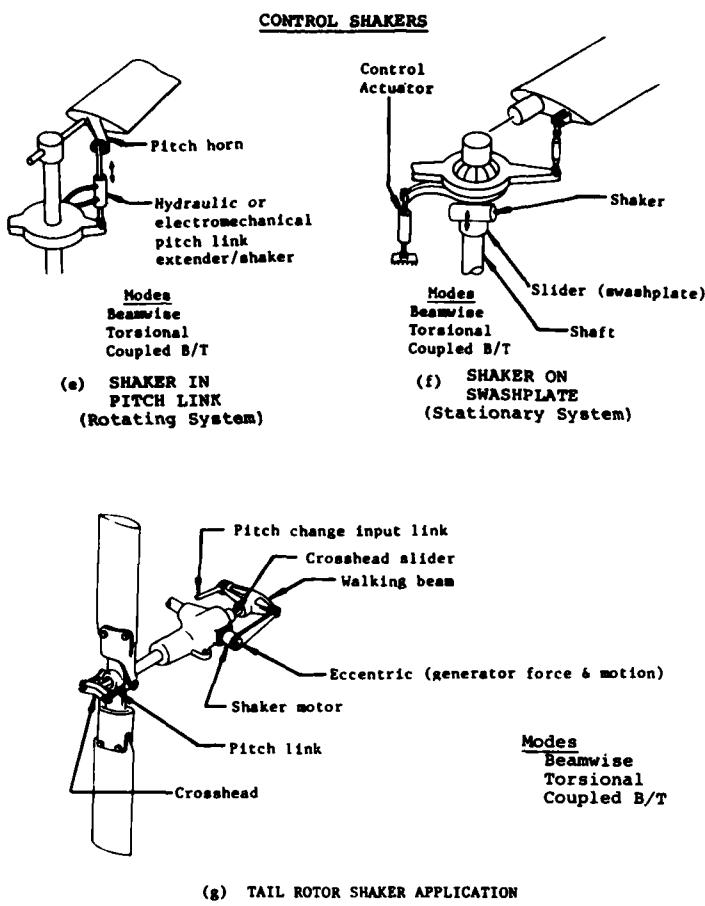


FIGURE 4-22 (CONTINUED). EXAMPLES OF SOME POSSIBLE SHAKER MOUNTING LOCATIONS

Applicability of the shaker type depends upon the inherent design features of each. Shakers mounted in the rotating system require a rotary transfer valve (slip rings) between stationary structure and the rotating hub. Fluid transfer mechanisms (hydraulic, pneumatic) tend to be bulky, have reduced reliability, and require excessive maintenance. The large diameter rotating seals that would be required have indeterminate failure rates. Therefore, frequent examination and replacement might be required. Oscillating masses by electrical means (solenoids) is a heavy method for shaking blades with the frequencies and magnitudes of forcing function required.

Design of the mechanical shakers in the rotating system is markedly affected by the centrifugal force field. The closer the location of the shaker to the axis of rotation, the lower the centrifugal force applied to the mechanism. Conventional shakers have been made with two opposite rotating weights geared to give a sinusoidally varying unbalanced force. A single rotating unbalance weight will also provide a suitable forcing function. Deicing response to a forcing function occurs at the natural frequency of the blade; i.e., a single rotating weight may force only beamwise motion because of the separation between beam and chordwise frequencies. The less complex single weight design was selected because of basic simplicity for the study to avoid the on-blade problem of retention of grease in the gears and bearings in the CF environment of the rotating blade. Fretting of antifriction bearings during nonoperating conditions of the shaker in the centrifugal field requires special attention; i.e., slow rotation of bearings or the use of nonfretting types. Table 4-5 shows that force levels necessary to excite a particular mode are less at a mid-span antinode or at the blade tip than they are at the first antinode from the hub. On the blade tip, the shaker may replace existing tip weights so the net increase in blade weight may be small or even zero.

Aerodynamic shaking may be provided either by flaps mounted on the blade at a particular spanwise location (antinode) or by cyclic or collective pitch change (dependent upon the mode excited). Flap aerodynamic forces are more effective at the dynamic pressure of the tip rather than at an inboard location, and structural modifications to a blade would probably be more easily accomplished at the blade tip (retrofit possibility); therefore, this location was selected. Oscillation of the control system to change blade pitch at a high frequency (8 per rev and higher) offers some difficulty. The control system/blade flexibility enters into the pitch response, making it difficult to control the phasing of the forcing function. The mechanism to force high frequency pitch change (hydraulic or mechanical) is complex and heavy. Also, the modal response from control inputs would contain a torsional element with unknown effects on deicing. These considerations caused selection of the tip-flap shaker as a candidate system.

TABLE 4-5. MAIN ROTOR BLADE MOUNTED SHAKER REQUIREMENTS, ASYMMETRIC MODE

Rotor System	Blade Station	Shaker Frequency (CPM)	Shake Force (Lb/Blade)
UH-1	28.8	2569	427
	57.6	"	338
	144.0	"	146
	288.0	"	174
AH-1	39.5	2571	757
	118.5	"	157
	264.0	"	188
CH-47	30.0	1888	394
	72.0	"	211
	180.0	"	145
	360.0	"	124
OH-58	21.2	2694	149
	42.0	"	99
	106.0	"	79
	212.0	"	51
YAH-63	42.0	2011	436
	137.0	"	245
	306.0	"	96

Shaking of the rotor system through a flexibly mounted tail or main rotor gearbox may be accomplished either by electrohydraulic or mechanical shakers. Tail rotor blades are usually not of sufficient size to permit the shaker to be mounted on the blade. Rotation speeds are high, and an individual shaker on each blade would require a heavy installation; normally, helicopter weight and balance considerations obviate heavy equipment located at the tail rotor station. Hydraulic shakers at the tail rotor either require a power source driven off the tail rotor drive system or suffer unacceptable line losses from main transmission-mounted hydraulic pumps. Weight/balance considerations exist here also; therefore, the mechanical shaker was selected for this use.

4.4.2.3 Key Results of Vibrational Deicing Investigation

(1) Vibrational deicing appears to offer excellent potential for ice protection for main rotor blades.

(2) Vibrational deicing has a limited applicability for present-day tail rotors. New tail rotor designs might include vibrational deicing. Analysis techniques do not reliably predict what will happen to the ice-metal bond in the high centrifugal force fields. There is need for more basic data in this area.

(3) Shaker control systems for accurate frequency control and phasing are readily achievable.

(4) Development and production costs for vibrational deicing systems are estimated to be cost effective in comparison with present electrothermal systems.

(5) A program including flight tests should be conducted to practically prove the concept and to obtain data to refine present analytical techniques.

(6) The test program should be a full-scale investigation on an instrumented aircraft using the dual mode deicing concept of main rotor mounted shakers.

(7) A shaker mounted in the blade tip might hold promise for an effective operational system.

(8) A portion of the program should consist of ground operation of the deicing system to ascertain the blade/gearbox/fuselage response to the various forcing function levels and frequencies suitable for deicing. Strain levels for nonrotating blades (ground deicing) necessary to deice would be investigated. Monitoring of fatigue stress levels to restrict forcing function values to reasonable levels should be conducted; the structural and aerodynamic damping should be measured. This program should be repeated for a rotating blade.

(9) Flight testing should be conducted under simulated icing conditions (spray tanker or Ottawa spray rig) using the ground data for selection of vibrational system operating conditions for both dual and single mode deicing. Deicing effectiveness of the vibrational deicing concept would thus be evaluated.

(10) System control operation and components should be tested and refined during both the ground and air phases of the program.

4.4.3 Electroimpulse Deicing Concept

The U.S.S.R. announced in 1972 that they had performed experiments with a new method of deicing. They referred to this concept as the electroimpulse (EI) concept and revealed that flight tests were in progress with experimental systems installed on Ilyushin 18 and 62 aircraft.

Reference 4-17 states that the EI system is protected by claims of the Russian inventors, and patents have been issued in Russia, France, Italy, Chile, Norway, and the United States. Sketchy reports of further independent research by various companies in various nations indicate that the EI concept is being further developed for various applications such as helicopter rotor blades. Results of these efforts are proprietary and not available for publication.

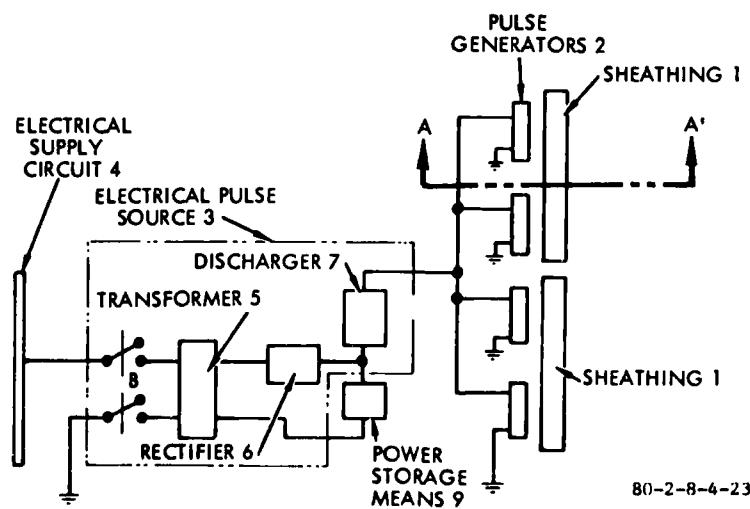
A description and assessment of the EI concept is contained in reference 4-16 and is provided below, in part, for convenience.

Electroimpulse deicing is based upon the technology of exerting an impactless mechanical shock to the aircraft skin in such a way that the ice is shed or precipitated in an inertial fashion. Photographs taken of the test surfaces during the instant of ice shedding show the ice to be almost exploded from the skin surface.

To accomplish the impactless shock, two (or possibly more) ways are considered. In both typical cases, a large quantity of electrostatic energy is used, but in one instance, the energy is dumped into one or more electromagnetic coils which are mounted in very close proximity to the aircraft skin. A steep wave-front is then developed in the coils, and this results in the skin moving away rapidly, within its elastic limits, to precipitate the ice. Electrically, the electrostatic energy is obtained from a capacitor bank which is charged over a period of 2 to 3 seconds at a moderately low power level of 3 to 6 kw. The energy, however, is discharged in a period of fractions of a millisecond, and the resulting current is measured in thousands of amperes. In this electrical method, the skin must be electrically conductive, since the impact is created by a heavy eddy current induced in the skin, resulting in a high repulsive force with the magnetic field causing the induction.

In the second method, electrohydraulic technology is used, wherein the electrostatic energy is discharged across electrodes which are immersed in a nonflammable, non-conductive liquid. The liquid is contained in a cavity of which the skin is an integral part. Mechanical shedding in this method is accomplished via the high pressures that are transmitted to the skin by the fluid.

To conserve power and energy in both schemes, individual coils or groups of coils are pulsed sequentially under the control of a commutator or programmer. The control and switching logic are design details that would be determined by the particular installation. In the case of the Ilyushin 18, the aircraft has been used as a test aircraft for about 3 years, and a hybrid system of conventional and electroimpulse systems has been employed. The electroimpulse system has been installed on the outer main wing sections and also on the horizontal stabilizer portions of the airplane. No definite details are available, but it is understood that there may be some 6 dozen coils in the Ilyushin 18 aircraft and that the power used is about 3 kw. These coils are estimated to be about 3 to 4 inches in diameter, spirally wound, and 3/8- to 1/2-inch thick. They are mounted on a nonmagnetic structure, and the distance from the skin is kept as small as possible, probably 1.0 to 1.5 mm. Figure 4-23 is a schematic of an electrical circuit of the system, and figure 4-24 depicts a possible rotor blade or engine inlet lip design. Details of the programming cycle are not available, but it is understood that the pulse time for each coil is much less than 1 second and is likely to be in the 0.3- to 0.4-millisecond class. The off-time is a function of the charge time between successive pulses, and, based on this being 2 to 3 seconds, the total cycle time would be in the order of 2 to 3 minutes.



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FIGURE 4-23. ELECTROIMPULSE DEICING-ELECTRICAL SCHEMATIC

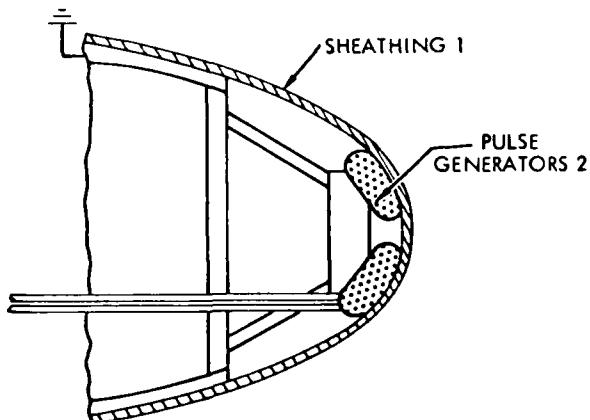


FIGURE 4-24. ELECTROIMPULSE DEICING-LEADING-EDGE ARRANGEMENT

Very significant weight and power efficiency advantages are claimed for the electroimpulse system. As applied to the Ilyushin 62, it has been estimated that the weight saving is of the order of 400 to 600 kg. These weight differences are presumably based upon a double-walled skin structure (for a bleed air system) and various bleed air penalties, such as engine thrust loss and change in specific fuel consumption.

Power estimates for a bleed air system on an Ilyushin 62 type aircraft are given as over 600 kw compared to about 6 kw for an electroimpulse system. While these are striking differences, the EI system would be better compared to an electrothermal system; and, for the Ilyushin 62, it would appear that this power requirement (for the electro-thermal system) would be approximately 45 to 70 kw. The facts, however, are that the differences between the EI and conventional deicing systems are indeed significant. The time-average power requirement for electroimpulse deicing is claimed to be approximately 0.0023 to 0.0046 w/cm² as compared to 0.31 to 0.62 w/cm² for a conventional electrothermal deicing system.

The principles of the EI system are basically sound, and they are not new, since some sheet-metal-forming processes have used the same principles for many years. However, the main attraction is that the EI system affords an electromechanical method of shedding ice, which means that the skin surface does not have to be heated above freezing - as is the case of the electrical- and bleed-air systems. As a result, the EI operates almost independently of outside air temperature (OAT) or liquid water content (LWC). However, there is some purpose (in different LWC conditions) in changing the cycle time so as to allow some ice mass to form on the surface before it is shed. It is implicit also in this type of system that there are no runback or insufficient-heat problems as experienced in many present deicing systems.

For optimum efficiency, the capacitor discharge time is controlled as a function of the natural frequency of the skin and is usually set to be less than one-fourth of the natural time period. By establishing a sharp wave-front pulse of energy in the electro-magnetic coil, the skin is rapidly displaced and caused to vibrate at its own frequency. When displacement is plotted as a function of time, it is seen (from figure 4-25) that maximum displacement occurs at one-fourth of the period; also, the ice must be precipitated while the skin is accelerating to its maximum rate during this period. Due to skin elasticity, the elastic deformation wave also travels from the point of its formation opposite the coil along the whole zone of the skin protected by the coil.

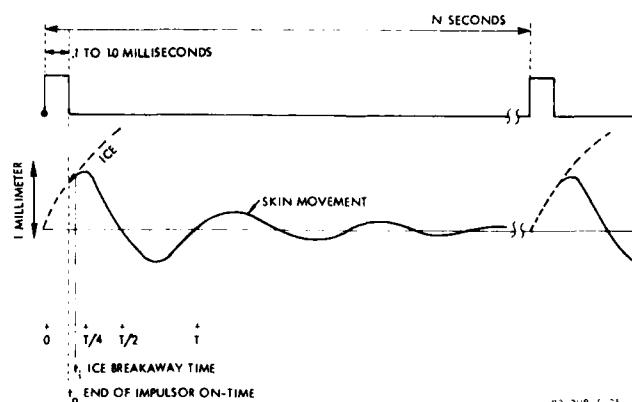
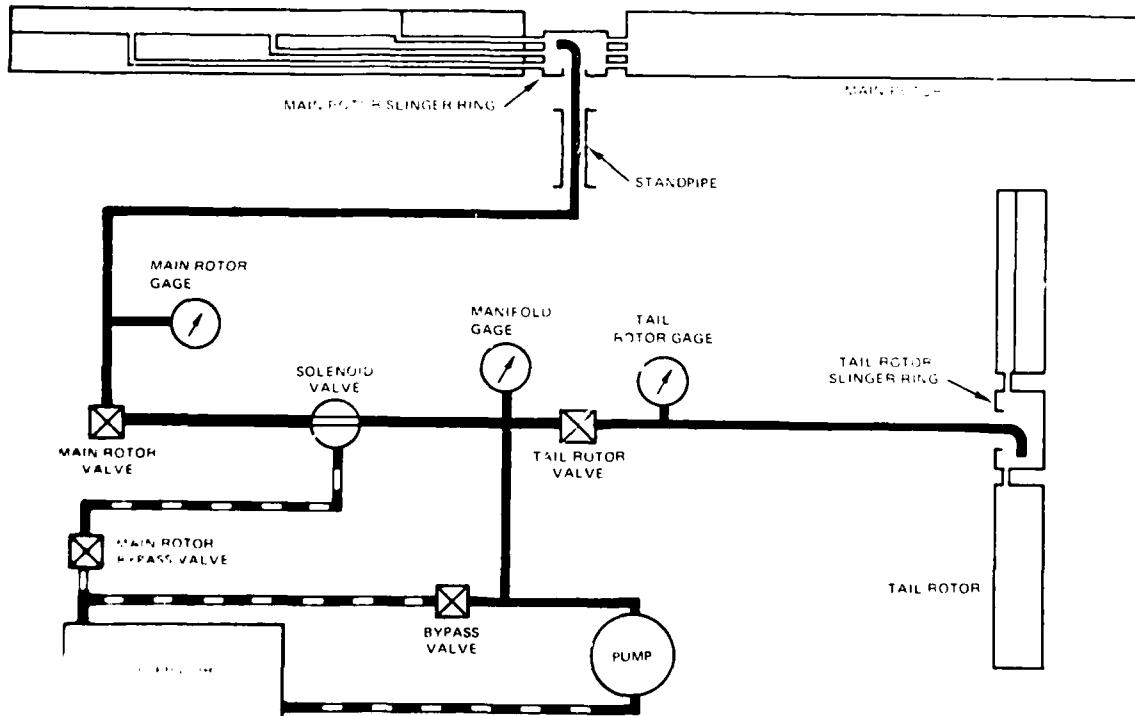


FIGURE 4-25. ELECTROIMPULSE TIME HISTORIES

4.4.4 Chemical Freezing Point Depressant

The chemical freezing point depressant system uses a fluid which lowers the freezing point when mixed with water impinging on the surface. The fluid, such as an alcohol (ethyl, methyl, or isopropyl) or glycol solution, is expelled at the stagnation line by means of holes, nozzles, or a porous panel. Figure 4-26 illustrates a prototype system installed and tested on a UH-1 helicopter in 1960-1961. It is composed of a fluid supply, a pump, a distribution arrangement at the point of icing, switches, control valves, and instruments. A slinger ring is used to transfer the fluid from a fixed nozzle to the rotating blade. The fluid is supplied to the blade by centrifugal force resulting from the rotational velocity of the slinger ring. Leading edge grooves distribute fluid to the holes in the stainless steel leading edge. The size and location of the injection holes in the leading edge are critical, and to achieve satisfactory deicing performance separate development and testing are required for each application to obtain a distribution system (whether it be orifices, nozzles, or porous panels). A selector switch located on the pilot's panel allows selection of mode of operation; i.e., continuous flow, cyclic flow, or system off. The main and tail rotor rates of flow are set by adjusting appropriate needle valves to obtain the pressure gage reading corresponding to the desired flow rate. A timer is used in conjunction with a bypass valve to cycle the main rotor flow on and off. The tail rotor flow is kept constant during the main rotor off-on cycle. A sensitive ice detector is required to ensure that the fluid depressant is turned on as soon as possible because the fluid may not be able to cope with a 2-minute ice buildup in heavy icing. Such a buildup may prevent uniform fluid distribution and may cause rivulets with a continued buildup between rivulets, thus increasing the profile drag and causing excessive vibration due to asymmetric shedding. Although relatively simple in concept, it does have some drawbacks when applied to airfoil anti-icing, such as difficulty in obtaining an even flow distribution in the presence of a variable external pressure field. It is an expendable system which requires resupply, and the sensitivity of the fluid distribution holes to clogging, particularly in a dusty environment, is also a drawback for helicopter operation. Depending upon the width of the fluid expulsion band, the system performance may be sensitive to aircraft attitude (angle of attack). Also, chemical systems have, at best, marginal recovery capability as evidenced by recent icing tunnel tests on a vendor proprietary fluid anti-icing system. Army helicopters, particularly in the lighter weight range, are designed to operate in a battle environment remote from the major supply base; thus, the logistic problem of maintaining a deicing fluid supply in forward areas for onboard replenishment as required represents a major liability of the chemical system. Another important point relating to the application of a freezing point depressant deicing system to combat helicopters concerns the vulnerability of the system to battle damage. Puncture of the fluid reservoir or fluid feed lines by bullets or shell fragments would cause loss of the entire system. In this respect, the freezing point depressant system is more vulnerable than the electrothermal concept because of its extension over a large space.



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Schematic of Chemical Freezing Point Depressant Ice Protection System

The theoretical value for the required rate of fluid expulsion can be easily computed. Basically, this theoretical value is a function of the type of fluid and its strength in the applied solution, of the ambient temperature and airspeed, and of the water catch rate. Figure 4-27 shows that, of the two extremes of the continuous maximum icing envelope, the maximum catch rate extreme (maximum LWC's) associated with a skin equilibrium temperature of 0°C and the minimum ambient temperature extreme associated with an OAT of -20°C (minimum catch rate), it is the latter that imposes more severe requirements. It is also seen that a 50 percent ethylene glycol-water solution is considerably less effective than the ethyl alcohol-glycerine mixture used in the Bell UH-1 experimental program. The ethylene glycol mixture, however, has been a common choice since it has several advantages: It is commercially available in large quantities, has a low volatility, and is not a fire hazard.

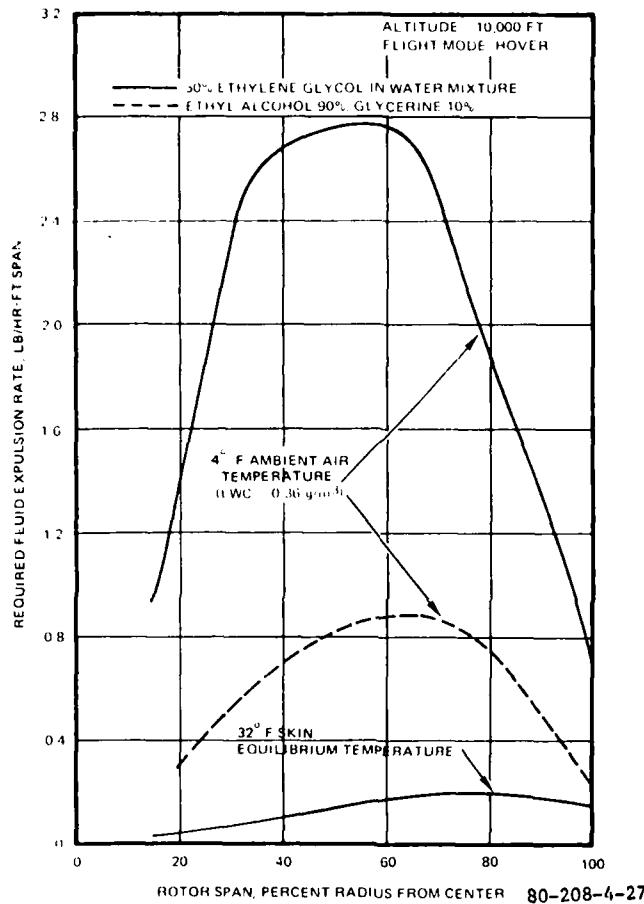


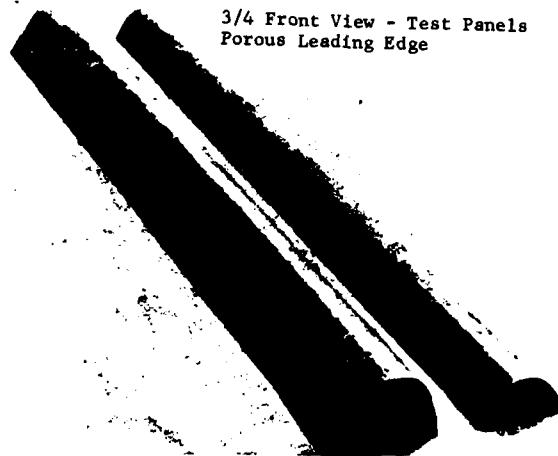
FIGURE 4-27. REQUIRED THEORETICAL FREEZING POINT DEPRESSANT FLUID EXPULSION RATE FOR UH-1 MAIN ROTOR BLADES

The UH-1 test data revealed that the actual total required fluid quantity was 142 kg/hr, which, in terms of average expulsion rate per unit span length of the main and tail rotors, amounts to 9.6 kg/hr/m span. This experimental value is higher than the maximum 60 percent span theoretical value of 6.4 kg/hr/m span (figure 4-27). The difference is due to the fact that, in practice, an ideal distribution of the fluid film cannot be achieved; thus, for the actual required average expulsion rate, it is necessary to apply a factor of 1.5 to the theoretically computed local maximum rate occurring at the 60 percent span station.

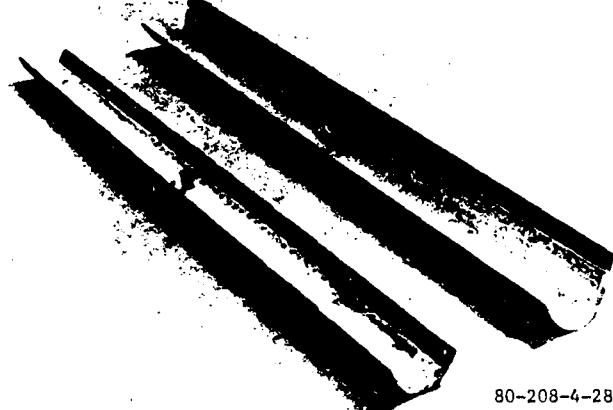
The (unheated) equilibrium temperature is determined by an energy balance between aerodynamic heating on the surface and evaporation of a water film. The ambient temperature associated with this balance decreases towards the blade tip, due to the increased kinetic heating, and hence, the "design" liquid water content varies spanwise. Since the water catch is proportional to the velocity and the liquid water content, the total catch is a maximum at some mid-span station.

To improve the coverage of the depressant on a surface subjected to icing, porous surfaces have been proposed as the injection device in an effort to uniformly distribute the fluid. The porous surface would be fabricated from furnace welded laminations of woven stainless steel wire. Micronic filters are used in the system to protect against internal pore blockage. Figure 4-28 shows a porous leading-edge distributor panel which can be manufactured in spanwise lengths up to 36 inches. The fluid deicing system has

3/4 Front View - Test Panels
Porous Leading Edge

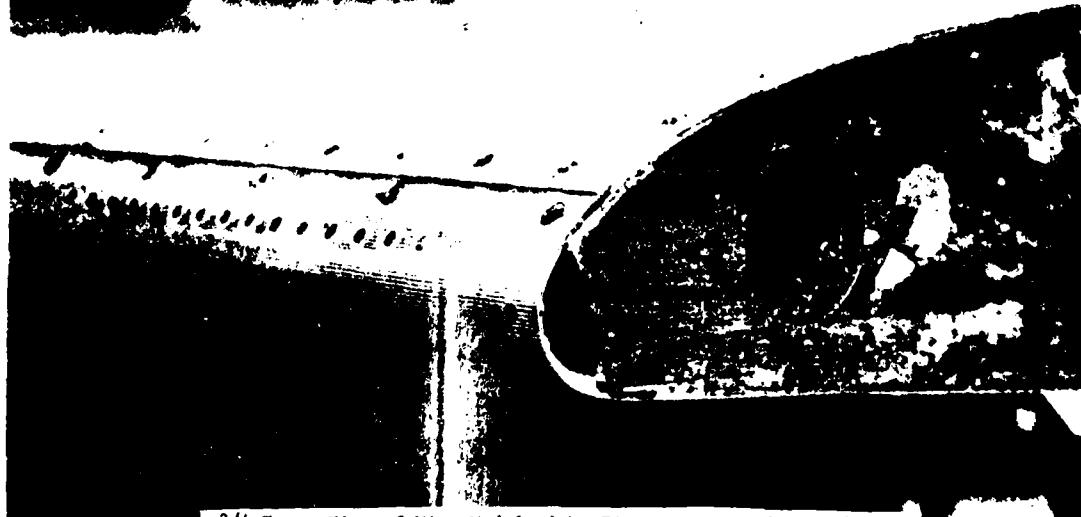
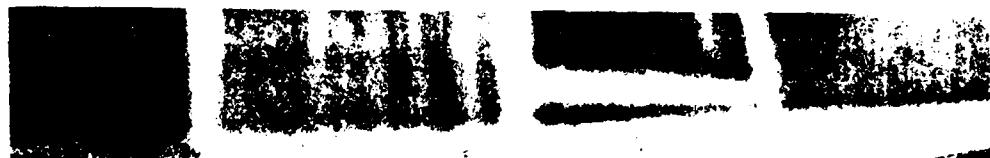


3/4 Rear View - Test Panels



80-208-4-28

FIGURE 4-28. POROUS LEADING-EDGE FLUID ANTI-ICING SYSTEM



3/4 Front View of Wing Model with First Test Panel Installed

80-208-4-29

FIGURE 4-29. POROUS LEADING-EDGE ICING TUNNEL MODEL

been tested in an icing tunnel. The model tested was a wing section without leading-edge sweep and rigidly mounted as shown in figure 4-29. Although the results from the tests indicate that shedding of the ice cap was not demonstrated, it is expected that a rotary-wing application would be conducive to better ice removal with the porous surface distribution system. The rotary-wing installations (as noted above) have consisted of orifices or nozzles in the leading edge of the main and tail rotor blades. These distribution devices were used to inject a freezing point depressant fluid into the stagnation region airflow to coat the blades for anti-icing protection, or between the ice-airfoil interface to weaken the ice bond to the blade and thus permit aerodynamic or centrifugal forces to remove the ice. In order to calculate the quantity of liquid depressant required, a datum temperature is used as a reference. The water catch rate is determined from the flight and climate conditions, the configuration of the airfoil, and the collection efficiency, which is also a function of flight and climate conditions as well as geometry of the airfoil. With the selection of a freezing point depressant (e.g., percentage of ethylene glycol in water) and its relation to the datum temperature, a flow rate of the depressant can be determined to prevent freezing of the mixture of the water catch and depressant. Distribution as described above plays an important factor. The theoretical approach assumes that the depressant completely covers the surface. However, experience has shown that this is not necessarily true, as aerodynamic and/or centrifugal forces can shed ice even though coverage has not been complete. In any case, excess depressant is required to assure that the ice is removed. The equations used in the theoretical approach are summarized as follows:

Datum Temperature (wet air boundary layer temperature, t_{ok} (in °C))

$$t_{ok} = 0.56 \left\{ t_0 + \frac{1.42 U_0}{gJ\bar{C}_p} \left[1 - \left(\frac{V}{V_0} \right)^2 \left(1 - Pr^{1/2} \right) \right] - 0.622 \frac{Ls}{\bar{C}_p} \left(\frac{e_{ok} - e_1}{P} \right) - 32 \right\} \quad (1)$$

Depressant Rate Required to Prevent Freezing (lb/hr-ft span)

$$W_f = \frac{0.68 G W_M}{X - G}$$

where

t_0 = ambient temperature °C

U_0 = flight speed, kt

V = local velocity along surface, m/s

V_0 = free stream velocity, m/s

Pr = Prandtl number (for air)

Ls = latent heat of evaporation of water, BTU/kg

e_{ok} = vapor pressure of air at surface of airfoil, mm Hg

e_1 = vapor pressure of saturated air at edge of boundary layers, mm Hg

P = pressure just outside the boundary layer, mm Hg

W_M = water catch, kg/hr/m span

W_f = weight of freezing depressant, kg/hr/m span

G = percent of freezing point depressant in final mixture—by weight

X = percent of freezing point depressant in the fluid mixture

g = gravitational acceleration constant, 9.8 m/sec²

J = Joule's constant, 778 ft-lb/BTU (522.8 m - kg/BTU)

\bar{C}_p = specific heat, BTU/lb °F (0.4536 BTU/kg °F)

4.4.5 Hybrid Deicing System

A hybrid deicing system is defined here as one that uses any combination of the deicing systems described in the previous sections. This discussion will be rather short because only three types appear to have been tested.

The most common hybrid deicing system is the combination of an ice phobic material applied to a pneumatic boot. The interesting point is that a little bit of ice phobic is apparently required to make the pneumatic boot deice well; figure 4-30 from reference 4-18 is typical of the effect of the ice phobic. The boot and ice phobic appear to work together as a deicer better than each works by itself, even after numerous sheds and rain erosion. A long test flight in rain and icing conditions of pneumatic boots on one of the old U.S. bombers was recently described (reference 4-19); alternating areas of the boot on the wing were coated or not coated with an ice phobic. This old test program clearly showed that only the coated areas shed ice well and reliably, shed after shed and in all kinds of weather. Although it has not been tested, it would seem - based upon the above discussion - that an ice phobic coating would permit an electrothermal deicer to shed better with less power, provided, of course, the coating is replaced often.

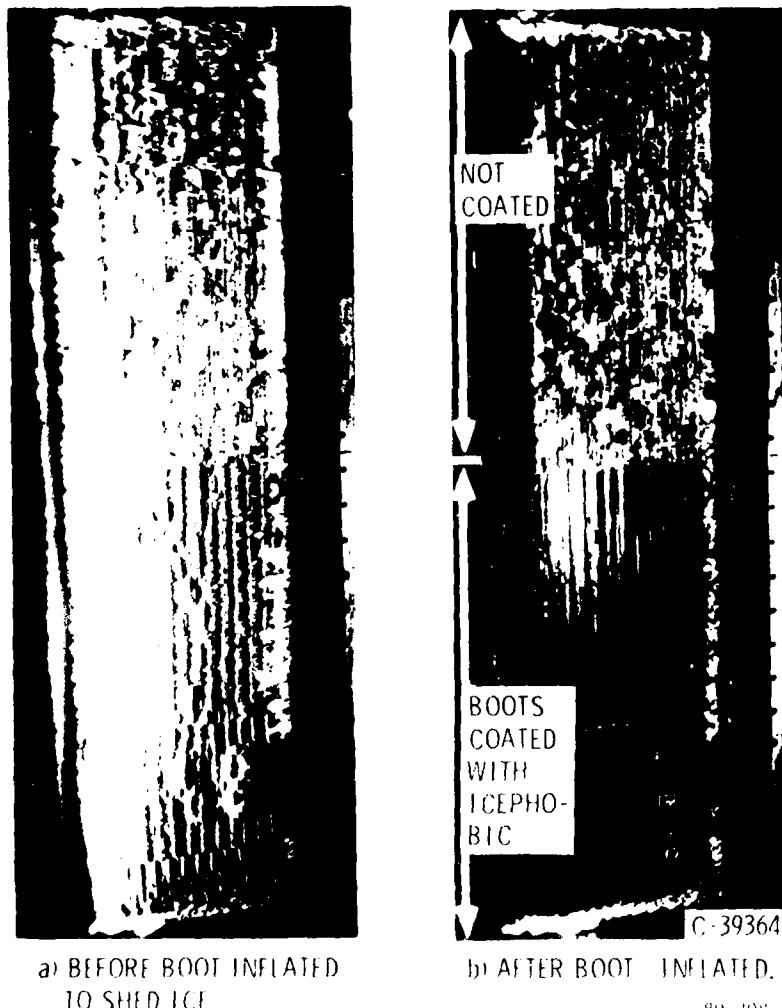


FIGURE 4-30. EFFECT OF ICE PHOBIC COATING ON THE ICE SHEDDING CAPABILITY OF A PNEUMATIC BOOT

80-208-4-39

Another hybrid deicer has been tested by the Royal Aircraft Establishment in an icing wind tunnel (reference 4-20). This hybrid consisted of an electrothermal mat over the small leading edge region and a paste (a jelled freezing point depressant) over part of the rest of the blade. When the electrothermal blanket was tested without the paste, there was a large build up of runback ice aft of the heater mat. But when the paste was applied, this ice was shed continuously. The advantage of this hybrid system is that the paste reduces the electrical power required for shedding while the heater mat on the leading edge avoids the excessive rain erosion of the paste in that region. This promising deicer has not been tested beyond that reported in reference 4-20 due to a lack of funding.

The paste aft of the electrothermal mat was also replaced by a permanent flexible surface. This hybrid deicer has been used successfully in other icing applications. Unfortunately, a lack of funds has precluded a proper test program.

4.5 OTHER HELICOPTER COMPONENTS

4.5.1 Engines

Protecting the engines from icing effects is a matter of primary importance for all helicopters. Anti-icing the engines alone, however, is insufficient, and protection normally can only be achieved together with an appropriately designed inlet system (airframe or engine mounted) which has to prevent ice accretion and, simultaneously, minimize inlet airflow distortion.

When turbine engines are operated in icing conditions, the following abilities are required:

- a. To withstand ingestion of ice particles of a certain size or prevent ice ingestion (i.e. integral foreign particle separator).
- b. To supply compressor interstage and/or discharge bleed air in sufficient quantity for anti-icing of engine parts (like front frame strut, guide vane etc.), and airframe-mounted inlet components.
- c. To tolerate a certain compressor airflow distortion that may be caused by ice accretion on the inlet system.
- d. To supply maximum required power and to respond quickly during rapid power demands while experiencing compressor bleed extraction and inlet distortion.

The engine must undergo icing and ice ingestion testing to determine the level of damage tolerance and anti-icing capability available from the basic (uninstalled) engine. These results will be used to establish the degree of inlet (airframe mounted) ice protection required. FAR Part 33, subpart E, states that engines must ingest without sustained power loss or required engine shutdown:

- a. Ice which has built up on the inlet system and engine face, due to a 30 second delay in anti-icing activation.
- b. Hail stones of a certain size (for exact definition see FAR Part 33, 33.77(f); for a typical test report see reference 4-21), and
- c. Water in the amount of 4 percent of engine airflow by weight.

Exception to this ingestion demonstration is stated if the engine incorporates a protective device that can stop and withstand the impact of foreign objects, and if such device will not obstruct the induction airflow.

Engine ice (and snow) protection may be accomplished with three main types of anti-icing:

- a. With alcohol spray as a freezing point depressant. This method, however, is no longer used in modern engines.
- b. Mechanically, by an inertial separator based on the principle of the momentum separation of liquid and solid particles from the air stream (reference 4-22). For that purpose, the inlet airstream is turned sharply, causing water and snow particles to continue undeflected past the compressor face (figure 4-31). The efficiency of such a system depends considerably on the icing parameters and on the bypass ratio: small droplets at the maximum engine power setting combined with the minimum flight speed represent the most stringent case. In most helicopter engine installations, however, mechanical ice protection can be provided only as part of the airframe installation, and not as an integral part of the basic engine.
- c. Thermally, with the heat supplied by compressor bleed or hot engine oil. The heated areas are generally the engine front frame, including struts and the inlet guide vanes. If the engine incorporates an integral foreign particle separator, the heat is supplied to the surfaces exposed to the primary airflow. Engines that incorporate hot oil anti-icing also utilize the heated surfaces as part of their oil cooling system. The disadvantage is that heat is being dissipated from these surfaces, even on hot days (unless the oil can be bypassed) with a resulting loss of engine power due to increased air temperature at the compressor inlet.

Engine compressor bleed air, while easily incorporated into the engine front frame system (figure 4-32), does entail a loss of engine power (or increase in fuel flow and turbine temperature to maintain constant power) when the bleed-air system is activated. The effects of bleed extraction depends upon the bleed pressure ratio and the bleed-port stage location.

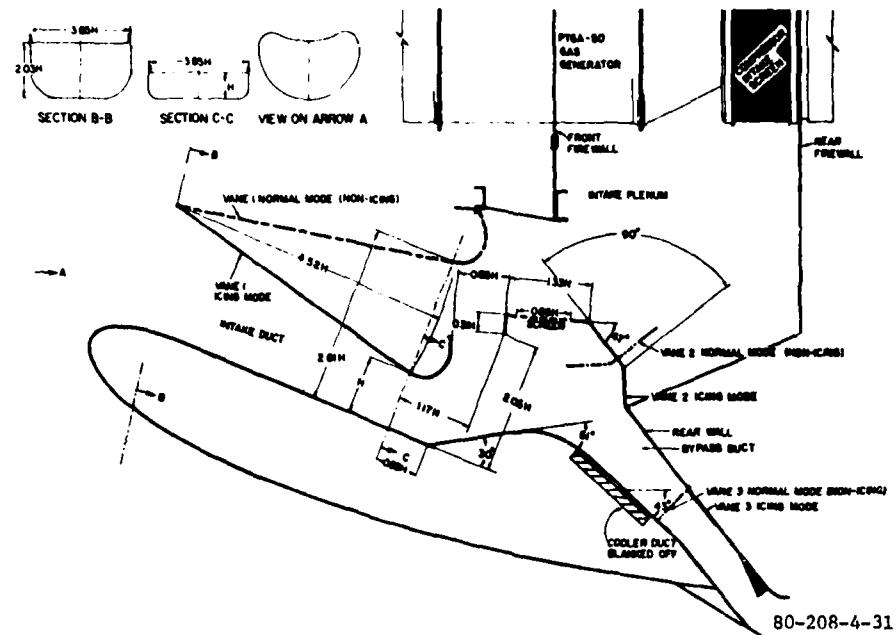


FIGURE 4-31. ANTI-ICING BY AN INERTIAL SEPARATOR, PT 6A-50 (FROM REFERENCE 4-21)

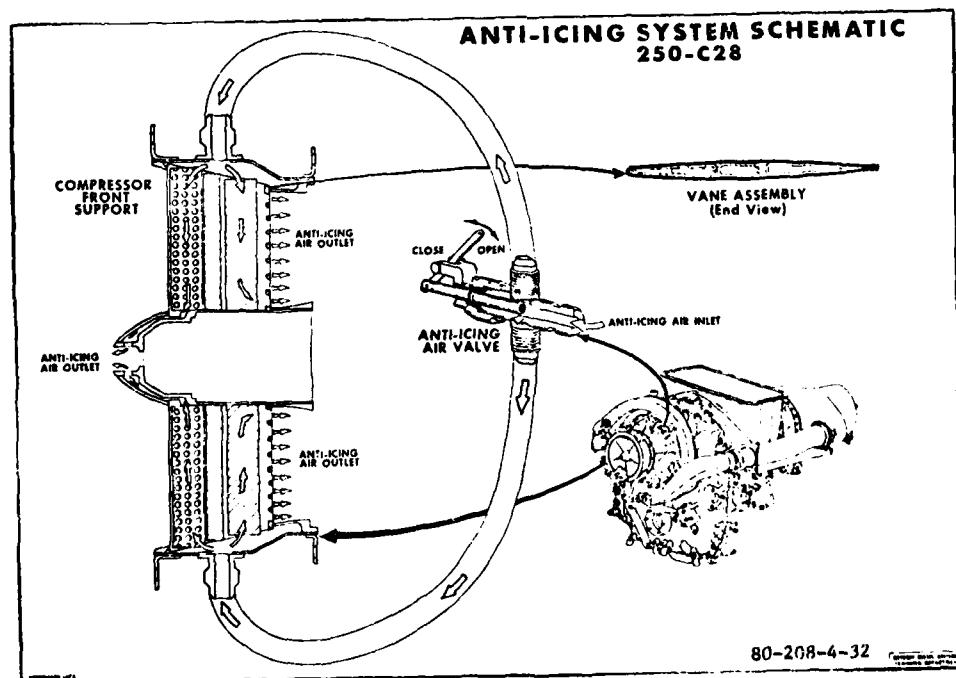


FIGURE 4-32. THERMAL ANTI-ICING SYSTEM WITH COMPRESSOR BLEED AIR

Furthermore, the kind of design of the area in front of the engines must minimize the possibilities for ice buildup to reduce the danger of sucking in larger pieces of ice.

4.5.2 Engine Inlets

The engine inlet is defined as that portion of the engine induction system supplied by the airframe. The inlet ice protection system must provide a means to:

- a. Prevent or minimize adverse (to the engine) ice buildup.
- b. Minimize airflow pressure loss and distribution under icing conditions.
- c. Safely withstand the impact of ice from external sources (airframe, rotors, natural) and prevent the ice, or at least those ice pieces large enough to cause damage, from reaching the engine compressor.
- d. Minimize power extraction from the engine (i.e., compressor bleed).
- e. Permit an alternate engine airflow path in the event the primary flow path becomes blocked.

Engine inlet configurations can be divided into the following groups:

a. Pitot or Dynamic Inlets. This inlet group has a high pressure recovery, but exposes the engine without any protection to external ice (and other foreign objects), see figure 4-33. It works well if the engine incorporates an integral separator. The anti-icing of the inlet surfaces can be achieved either by compressor bleed or electrical heating elements.

A combination of both types is also possible (example, Advanced Attack Helicopter). When using electrical heating elements, the inlet area should be divided into individual, independent sections in order to permit the installation of an optimum heat distribution and to be failsafe.

b. Forward Facing Internal Inertial Separator Inlets. This inlet group provides engine protection from foreign objects by the use of particle deflection or particle "swirl" (similar to vortex principle). The inlet surfaces require anti-ice heat which can be supplied by compressor bleed or electrical resistance elements. Because of the varying surface contours, fiberglass construction is generally chosen over metal and, therefore, electrical heating can be incorporated easily.

c. Forward Facing External Inertial Separator Inlets. This inlet group uses a similar approach to group b for engine protection, namely deflection of the particles. The "mushroom" type inlet is an example, see figure 4-34. This method provides protection, at least to a certain extent, and reduces the danger of sucking in ice shed from the fuselage. However, ice forms on the "mushrooms" themselves, in particular, if they are not heated and this ice in turn endangers the engines, depending on the geometry involved. It would be therefore of an additional advantage if the exposed surfaces (in particular, the forward facing surfaces) could be heated in the anti-icing mode. The deicing mode may be practical if it can be demonstrated that the shed ice will not enter the compressor airstream, or that the ice pieces are tolerated by the compressor. The heat can again be supplied to the inlet surfaces by compressor bleed or electrical power.

d. Enclosed (Vortex Tube) Inlets. This inlet type features a full compartment or enclosure forward of the engine compressor inlet in which a number of sideways facing vortex (swirl) tubes are installed. The internal swirl vanes of each vortex tube cause entering particles to centrifuge to the outer tube wall where secondary air (usually supplied by an auxiliary blower) draws the particles away from the primary (engine compressor) airflow. The principal reason for this type of inlet installation is to protect the engine during sand and dust operations. Protection from engine icing is also a feature of this installation because of the water droplet inertial effects caused by the sideways facing vortex tubes (i.e., ice tends to form on the outer tube edges without fully blocking the tube entrance). An example of this "multipurpose air intake" can be seen on the Puma (reference 4-23).

Emergency air provisions (and ram air during forward flight) can be incorporated into the design by use of forward facing movable plugs or doors. Anti-icing is not generally used with this inlet configuration. However, provisions for maintaining an ice-free emergency air door or plug can be designed into the system.

e. Forward Facing Inlets with Shields. These inlets have generally been derived from forward facing inlet configurations where the need for foreign object protection (in particular, ice shedding from forward locations) has been demonstrated. The shield (or deflector), in most cases, is no more than a section of sheet metal located forward of a simple bellmouth inlet fairing (as an example see the Sea King with the Sikorsky foreign object deflector, (figure 4-35)). Generally, no anti-ice heat is used on the shield; the ice is allowed to build up and break off on the forward side of the shield.

Tests have shown (figure 4-36) that, with a deicing fluid exuded from porous strips in the front face of the shield, a remarkable reduction in ice accretion can be achieved. Similar results may be achieved by treating the surface with ice phobic coatings but test evidence is not yet available.

Potential icing problems may occur when using a shield in:

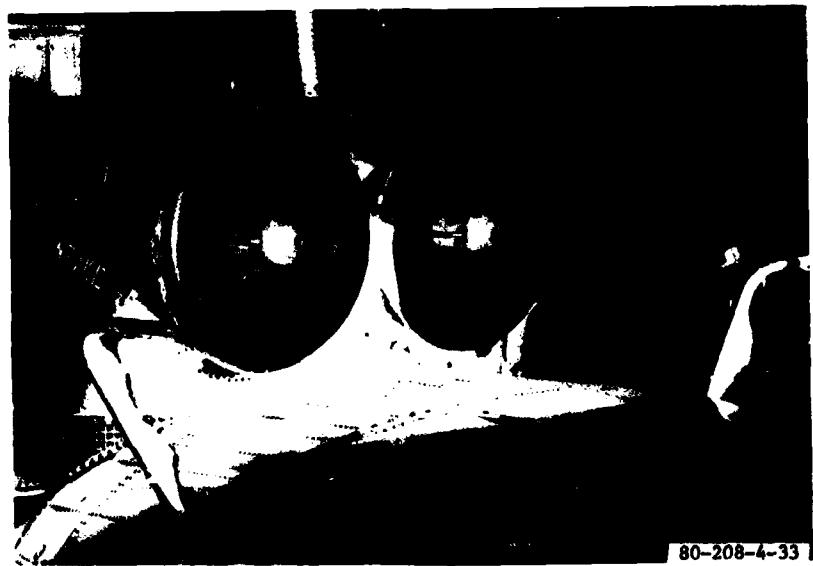
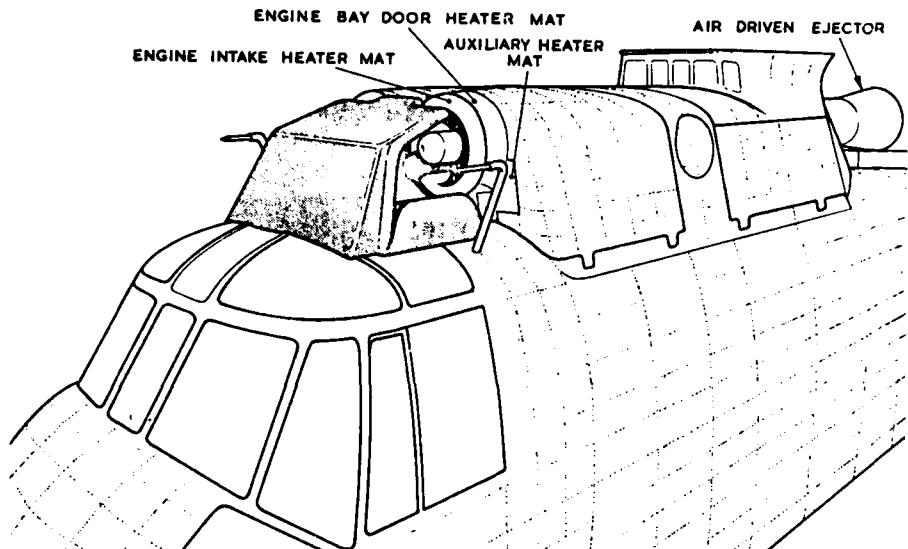


FIGURE 4-33. PITOT OR DYNAMIC INLETS (SEA KING WITH GNOME H 14 00 ENGINE AFTER 30 MINUTES AT $0,6 \text{ g/m}^3$, -10° C and 120 KNOTS)



FIGURE 4-34. SEA KING WITH MUSHROOM INTAKES (AFTER 15 MINUTES AT $0,77 \text{ g/m}^3$, -4° C and 120 KNOTS, RIGHT INTAKE HEATED, LEFT UNHEATED)



80-208-4-35

FIGURE 4-35. SEA KING WITH SIKORSKY FOREIGN OBJECT DEFLECTOR
(REFERENCE 4-24)



80-208-4-36

FIGURE 4-36. FOREIGN OBJECT SHIELD TREATED WITH DEICING FLUID (AFTER 27 MINUTES AT 0,6 g/m³ and 3 MINUTES AT 1,2 g/m³, -10° C, 90 KNOTS)

1. Low speed flight or hover, if supercooled water droplets impinge on the aft side of the shield and

2. At higher speeds when ice accretion occurs particularly around the edges of the shield.

Aerodynamic contours may be incorporated into the shield design to improve both the external and internal airflow paths.

f. Side Facing Inlet. In this case, the mechanical protection is achieved by turning the suction direction.

Sideways facing intakes with intake heater mats have given encouraging results, (reference 4-24 and figure 4-37). It can be advantageous if the mats are divided into a number of separate sections for optimum heat distribution.

g. Plenum Chamber Inlets. Plenum chamber designs can be used in submerged engine installations in combination with side facing or shielded intakes. The supercooled water is deposited on the shields and the engine sucks its air from the protected chamber. Examples for this design are the plenum chambers of the Sikorsky S76 (Spirit), the Agusta A-109, and the BO 105, (references 4-25 and 4-26, figure 4-38).

The plenum chamber normally reduces or eliminates the need for anti-icing. However, it may offer inadequate protection in cases where detached lumps of ice can be ingested by the compressor. Ingestion of snow also may present a problem, particularly if the snow contacts a warm surface (unless enough heat is supplied to completely melt the snow). The engine inlet may therefore be protected by an additional screen. But, unless it can be demonstrated that the screen will not fully ice, provisions for bypass engine air must be incorporated. A heated screen could be installed, but the energy requirements have generally shown that this is not a viable choice.

4.5.3 Windshields

Anti-iced windshields are essential for flights under icing conditions. Depending upon the certification status of the helicopter (certified for one or two pilots for flights under IFR), the minimum field of view requirements and the flight missions which have to be performed, the windshields in front of one or both pilots must be anti-iced. A&AEE has concluded that, irrespective of the number of pilots, both sides and any center screen should be anti-iced to give adequate flight safety. In all cases, the anti-iced parts must permit good visibility, in particular, during runway approach and hover flight (figure 4-38).

Nowadays, anti-icing the windshields is normally achieved by electrothermal heating. For that purpose, an extremely thin, electrically conductive layer is bonded between two acrylic or vinyl layers. Depending on the mission requirements, the total windshield thickness amounts to 4 to 7 mm. The temperature range to be covered amounts to approximately -30°C , which requires a heating capacity of approximately 0.4 to 0.6 W/cm^2 . Heating the windshields must be automatic, but reliable protection against overheating the material is mandatory.

A second possibility to protect the windows against ice is the use of liquid freezing-point depressants. The deicing effect, however, is not as good as that of the electrical heating system, since deicing is often only partial and the windshield wipers are consequently often damaged. Additional difficulties often occur due to clogged or frozen jets.

4.5.4 Antennas

Considerable quantities of ice may be deposited on antennas during longer flights in icing conditions. As a consequence, the following problems may arise:

a. If the antenna is located in front of the engine intake, the danger exists of detached pieces of ice being sucked in by the engine.

b. Long whip antennas, if covered by a large amount of ice, offer such a large area of exposure to the air stream that they may come into contact with rotating parts (e.g., tail rotor).

c. Long wire antennas (e.g. for ADF) when covered by sufficient ice are subjected to such a high mechanical load that they can break. A detached part may come into contact with rotating parts.

d. The efficiency of certain antennas may be reduced, in particular in the case of wet ice.

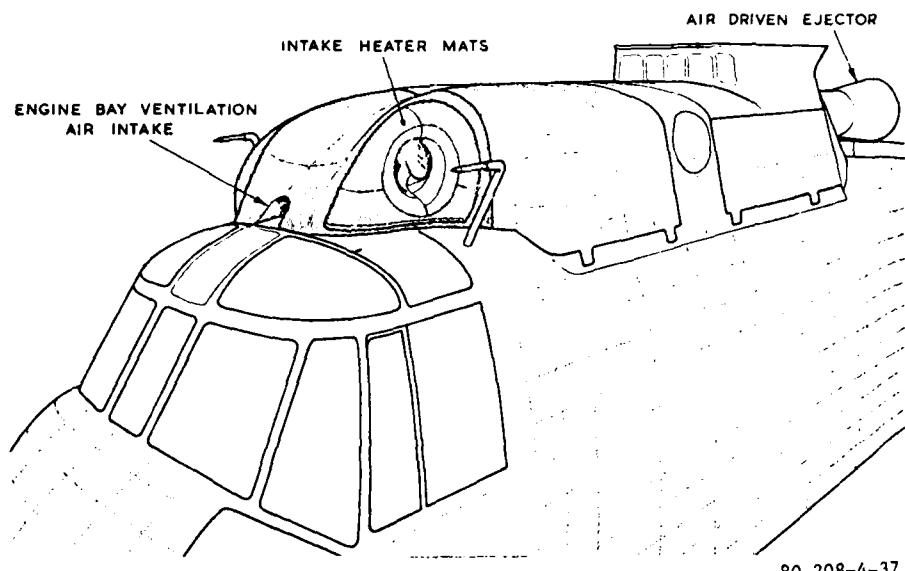
e. The possibility exists of ice shed from an antenna coming in contact with and causing damage to main or tail rotor blades.

Deicing the antennas is extremely difficult. For this reason such problems must be overcome during the design phase:

a. Basically, no antenna should be mounted in or near the suction area of the engines, in order to avoid the danger of damage to the engines due to detached pieces of ice.

b. Whip antennas must be attached or shortened so that they may, under no circumstances, come into contact with rotating parts.

c. Antennas whose performance is reduced due to the formation of ice must be



80-208-4-37

FIGURE 4-37. SEA KING WITH SIDEWAYS FACING ENGINE INTAKES (FROM REFERENCE 4-24)



80-208-4-38

FIGURE 4-38. ANTI-ICING OF THE RIGHT-HAND WINDSHIELD AFTER 1 HOUR IN NATURAL ICING CONDITIONS

mounted near the exhaust gas jet.

If no particular design measures to avoid the formation of ice are feasible, and deicing a certain type of antenna is necessary, using an appropriate paste represents the only current solution. Deicing with paste (ice phobic coating or material), however, exhibits the great disadvantage of necessitating constant maintenance work. Work to find alternatives is being pursued by the U.K.

Comprehensive tests for deicing homing antennas on the Lynx are described in reference 4-27. It was found that only a mixture of anhydrous calcium chloride in alcohol soluble nylon was fully effective.

4.5.5 Weapon Subsystems

Ice protection of the target designation system and the night vision system is indispensable for military helicopters with all-weather mission requirements. Electrical heating, similar to that used for windshields or hot air flow, is the only applicable method of ensuring the necessary clear visibility through the sights.

The United States Army's Advanced Attack Helicopter (AAH), the YAH-64, carries a nose-mounted visionics package which includes a Target Acquisition/Designation System (TADS) and a Pilot Night Vision System (PNVS). The total AAH weapon system has a requirement to be capable of flying through icing conditions and to be ready to fight upon emerging from these conditions. For the TADS/PNVS, this requires keeping the optical windows clean and assuring that the turrets are free to slew in azimuth and elevation.

The ice protection system for the TADS/PNVS as presently configured utilizes electrothermal anti-icing, electrothermal cyclic deicing, and mechanical shielding to allow the unit to continue to operate after exposure to icing conditions. The reader should note that, as of this writing, the TADS/PNVS and its ice protection system is still in the development stage and the final configuration is subject to change based on the outcome of the design support and qualification tests. Figure 4-39 gives a summary of the critical clearance areas on the TADS/PNVS where the ice protection system must prevent or overcome ice bridging from fixed to rotating structure. Also illustrated in figure 4-39 are all optical surfaces on the front face of the TADS/PNVS unit which must be protected. In addition, there is a boresight module window on the back bulkhead which must also be treated since the unit is capable of boresighting in flight.

The shaded area in figure 4-40 highlights the areas where ice accretion is anticipated. These areas were defined during a 1/4-scale model test program. The testing medium was india ink. While the shortcomings of this approach are recognized, a full scale icing tunnel test was impossible during the early development stage and the 1/4-scale test was felt to be a worthwhile risk reduction effort. Note that most of the forward facing areas are affected, as well as the shielded aft bulkhead where the boresight module window is located.

The ice protection provisions on the TADS/PNVS include the following features:

- a. All exterior optical surfaces are electrothermally anti-iced. See figure 4-41.
- b. Interfaces where relative motion occurs between rotating and fixed structures are protected by mechanical shields. See figure 4-41.
- c. Nontransparent areas which accrete ice are protected from excessive build-up by a cyclic electrothermal deicing system.

The deiced area is divided into zones as shown in figure 4-42, which are powered cyclically. The interfaces between zones are continuously anti-iced by cutting lines.

The TADS/PNVS with a prototype ice protection system installed was successfully tested in the NASA-Lewis Icing Research Tunnel in June 1980. Design refinements will occur as a result of this test and a revised version will be flight tested on the AAH aircraft during winter 1980-1981, with additional refinement occurring as a result of this test.

Weapons must similarly be protected against the formation of ice, should ice impair their operation. For example, since the formation of ice on the control surfaces of rockets would considerably impair their flight mechanics and thus their trajectory, they must be protected during carriage - either each rocket in a separate container or several together in one launcher. The front end of the container may be protected by means of a thin plastic cover which is pierced by the weapon when fired.

4.5.6 Miscellaneous

- a. Pitot-Static Tubes. Every helicopter which is certified for flights under icing conditions must have a dual anti-iced pitot-static system. There are two separate specifications:

1. For commercial application, FAR 25 intermittent maximum icing conditions specifies 1.0 g/m^3 at -30°C .

2. For military application, MIL-P-26292 specifies 1.5 g/m^3 at -35°C at an altitude of 10,000 feet and a speed of Mach 0.6

The pitot-static tubes are heated electrically to provide wet surface conditions for these specified stringent ambient conditions. Presently-used power intensities normally provide a more than adequate heating margin.

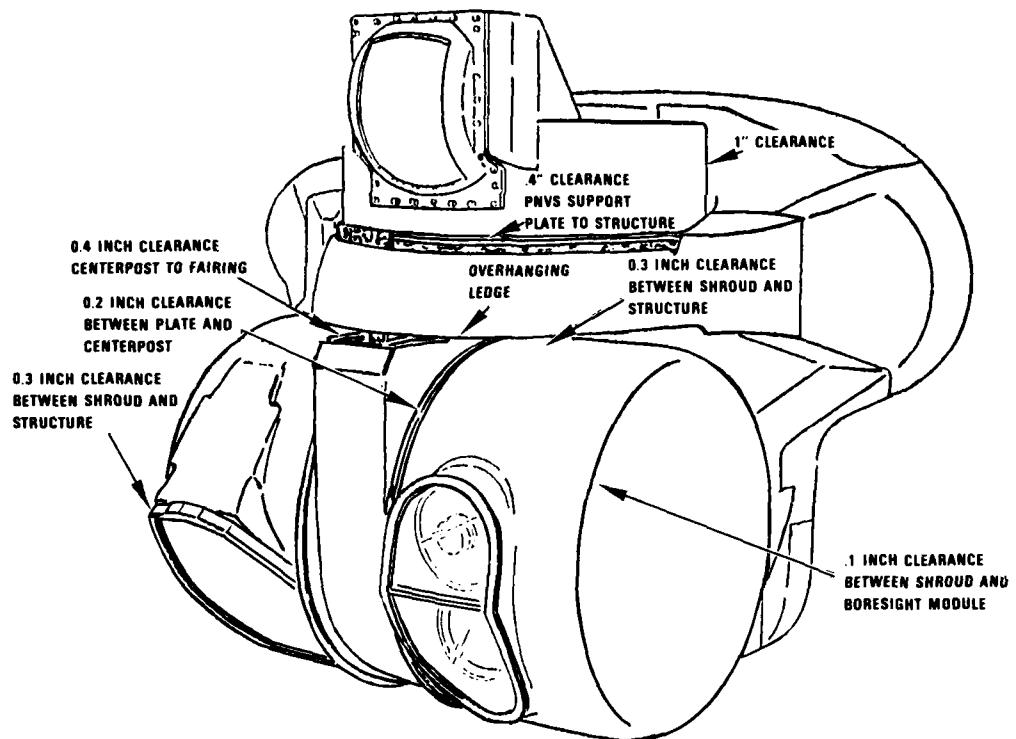


FIGURE 4-39. CRITICAL PNVS AND TADS CLEARANCES

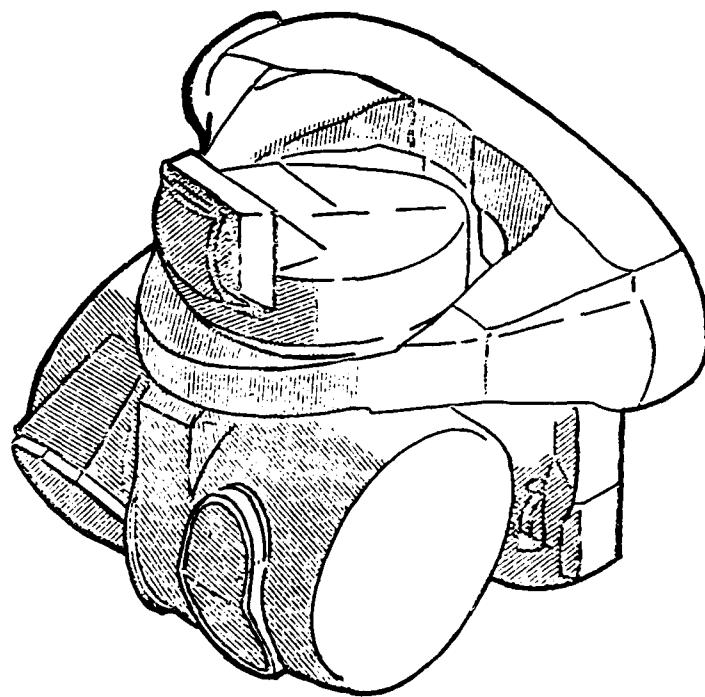


FIGURE 4-40. ANTICIPATED AREAS OF ICE ACCRETION

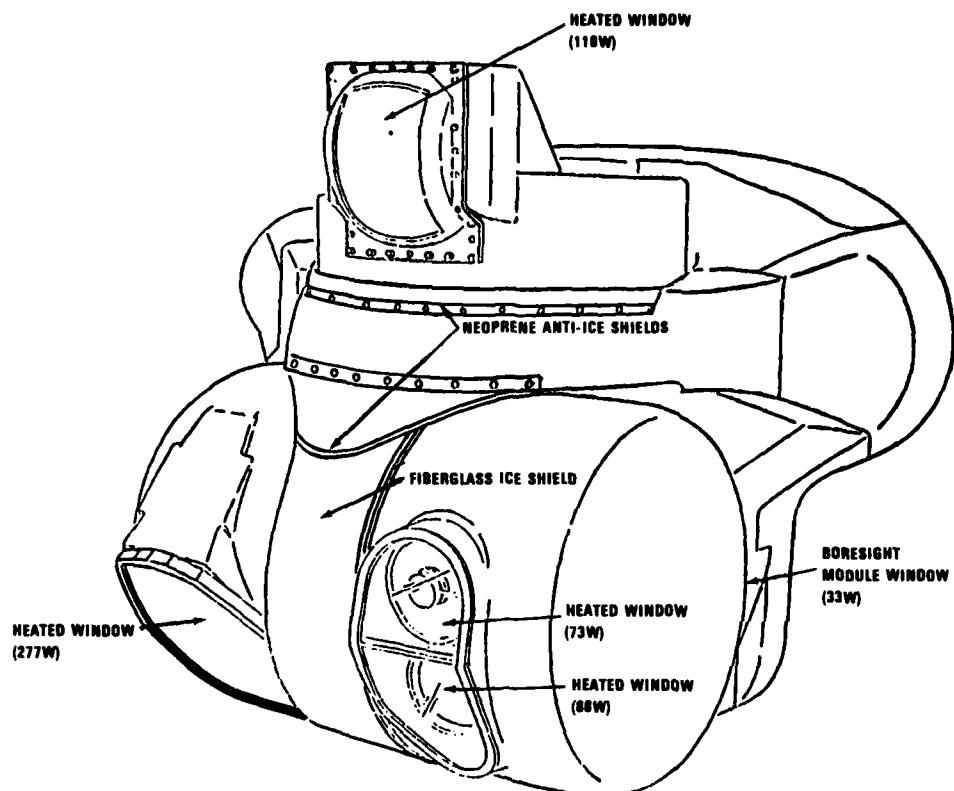


FIGURE 4-41. STRIP HEATERS AND ANTI-ICE SHIELD

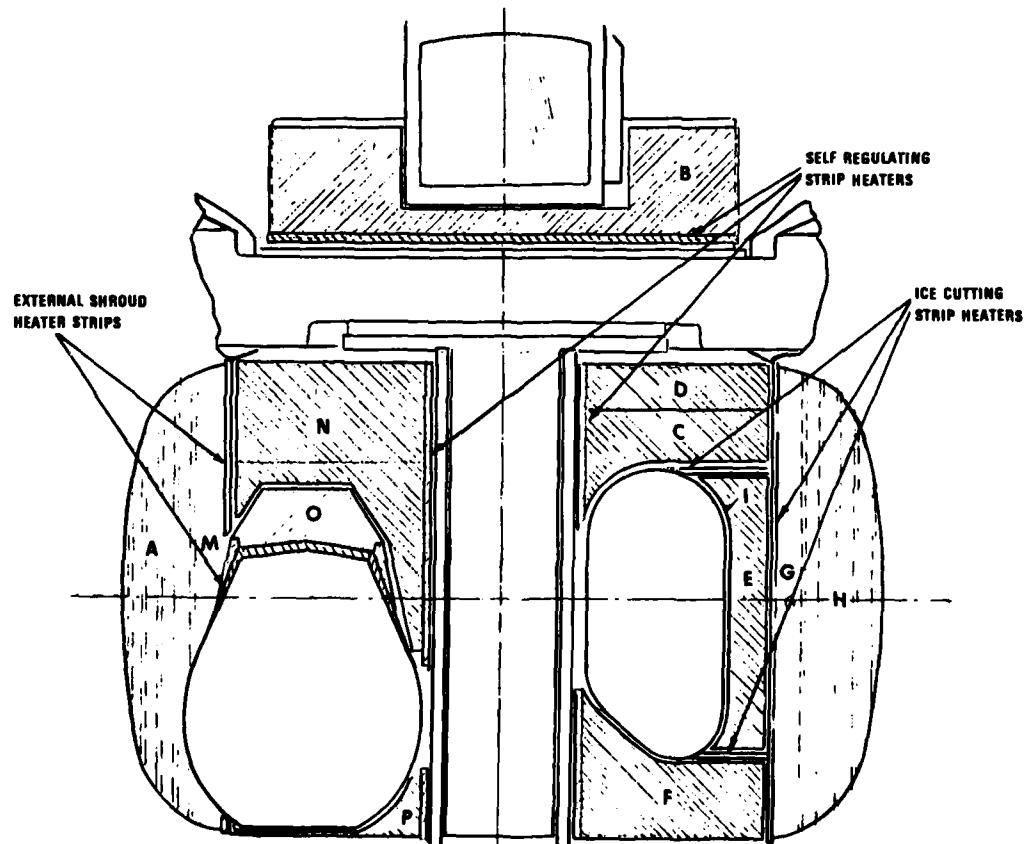


FIGURE 4-42. STRIP HEATER LOCATION FOR TURRETS

In cases where fail-safe, static system anti-icing is not possible, a switch-over to cabin pressure is mandatory.

Pitot and static lines should be designed and installed in such a way that water entrapment is not possible, to avoid blocking of the lines due to ice.

b. Rotor Hub, Blade Attachment, and Exposed Controls. Non-rigid rotors sometimes have problems with icing of the droop stops. In those cases, a cover or other suitable protection may be necessary.

Servo pilot valves have a tendency to freeze in cold weather, due to water entrapment or condensation. Servos should be designed in such a way that blocking cannot occur.

From testing conducted to date, it has been concluded that helicopters with a rigid rotor system do not need protection of the rotor hub (figure 4-43).



80-208-4-43

FIGURE 4-43. ROTOR HUB AFTER SEVERE ICING TESTS IN THE CLIMATIC CHAMBER

c. Horizontal Stabilizer. Ice accretion on the horizontal stabilizer can affect the static and dynamic stability of the helicopter. Therefore the need for ice protection must be established through analyses and tests.

Tests under natural icing conditions, with some helicopters, have shown that, depending on the design, the tail rotor draws the warm exhaust gas jet over part of the stabilizer so that, at most, only one half of it will ice up.

Should flight tests on a new type of helicopter show that flight safety requires a completely ice-free stabilizer, various possibilities can be considered:

1. Electrical heating

2. Pneumatic deicing (inflatable boots) as it is used on the wings and tail units of fixed wing aircraft.

3. Electrical vibration excitation. This would require a considerable effort in design and development, and the feasibility is not yet demonstrated.

4. Paste application. Some experiments are in process, but the results are not yet known. Furthermore, this method entails the disadvantage of constant maintenance.

d. Tank Vents. A clogged air vent of a fuel tank leads within a short period to an engine failure and in some designs could lead to collapse of the fuel cell. Appropriate design measures must therefore ensure that clogging of the air vent due to ice (in flight or after a landing in deep snow) is prevented.

e. Landing-Gear Doors. Care must be taken that the landing-gear doors of helicopters with retractable landing gears cannot freeze (reference 4-26). The design can be assisted by proper use of teflon seals in some applications.

f. Icing Tests with Radomes. Reference 4-16 showed that the drag penalties due to ice accretion on radomes are relatively small. The reduction of the forward looking radar (8,000 to 12,000 MHz, x-Band) transmission efficiency due to ice is less

than 20 percent; the effect on Doppler radar (12,000 to 20,000 MHz, K-Band) is greater. Installation of a pneumatic boot gives a reduction in efficiency of approximately less than 20 percent, while freezing point depressant anti-icing would cause a 10 percent reduction. However, both systems would also give a reduction in efficiency in clear air operation. Furthermore, the Doppler radar is downward looking and traditionally located on the bottom surface of the fuselage with only a slight protrusion into the airstream. It is therefore concluded that no radome ice protection system is necessary or justified.

4.6 OPERATIONAL CAPABILITIES

4.6.1 General

The growing use of the helicopter is such that operational limitations that used to be insignificant are now becoming penalizing and will be unacceptable in the future. One of the most operation-restricting factors is the risk of encountering icing conditions; numerous civilian or military users are demanding aircraft capable of flying in potential or actual icing conditions.

Helicopter missions vary greatly with the user. They range from IFR flights on routes with quite predictable weather conditions to VFR flights over regions where weather conditions are little known and where navigation aid is scarce. The former case corresponds to airlines operating helicopters on regular routes. In addition to safety, they require cost-effectiveness. The latter case corresponds to operations by the military or by civil protection bodies. The priority in that case is the maximum availability of the aircraft (after safety, obviously). It is therefore apparent that the operational requirements (needs) for helicopters vary greatly, and are set by the users. A knowledge of the requirements of civilian or military users makes it possible to adapt the operational capabilities of helicopters to such requirements (see section 1).

Only recently have helicopter operators voiced their concern for an increased operational capability for their aircraft, and helicopters capable of flying in icing conditions are few. Under such conditions, with diminished operational capabilities, the use of the helicopter is contingent upon the sophistication level of the ice protection systems.

Helicopters capable of flying in icing conditions can be split into two categories. First, helicopters with a minimum protection level allowing partial flight in icing conditions. Second, helicopters with complete protection against icing, including rotor protection. Helicopters falling into this category are capable of unrestricted, all-weather flying.

Table 4-6 shows the ice protection devices to be found on various protected helicopters.

TABLE 4-6. HELICOPTER ICE PROTECTION SYSTEMS

Engine or Air Intake Protection	Windscreen	Main Rotor	Tail Rotor	Ice Detector	IFR Equipment	Weather Radar	Lightning Protection
WESSEX	X	X	X	X	X		
UH-1H	X	X	X	X	X	X	
BO 105	X	X	X	X	X	X	
S-76							
SA-365N	X		X			X	
SEA KING	X	X			X	X	
LYNX	X	X				X	
CH-124	X	X	X	X	X	X	
PUMA	X	X	X	X	X	X	X
CH-53	X	X				X	
UH-60	X	X	X	X	X		?
CH-47	X	X			X		?

In a description of a protection system, it is necessary to detail the following points so that the operational capabilities of the helicopter can be estimated:

- authorized flight envelope (altitude, temperature, speed...),
- work load for the crew, and
- loss of performance of the aircraft due to the installation of the protection systems and to the ice deposits.

4.6.2 Experimental Aircraft

Considering the type of operation for which they are intended, these aircraft are fitted with important measuring equipment, particularly instruments used to measure the

concentration of liquid water and the diameter of drops. In certain cases, when the evolution of those parameters is known, the operating limits of the aircraft can be considerably widened, even if the protection systems are not complete. Moreover, the aircraft are provided with a highly trained test crew, thus enlarging the operational envelope of those aircraft.

Generally speaking, the tests performed under icing conditions, with experimental aircraft, aim at:

- understanding the icing mechanisms on the helicopters,
- discovering and developing protection systems, and
- finding the efficiency limits of those systems.

The purpose of experimental flights is to specify the origin of the operational limits of the aircraft when their rotors are not protected, due to:

- prohibitive vibration,
- power increase, and
- impossibility of initiating autorotation.

It is not possible to specify the complete operational limits of these research aircraft, since most of the above mentioned testing is in general at a few specific cases only (references 4-28 and 4-29). The experimental flights only show that the enlargement of the flight envelope for the helicopters depends on the protection of rotors.

The work load of the crew for an experimental helicopter cannot be used as a criterion of operational capability, since the number of crew members is generally higher than on helicopters operating under normal conditions.

Examples of icing effects on performance are given in figures 4-44 and 4-45 and table 4-7.

4.6.3 Aircraft Under Development

The case is the same as that of experimental aircraft - it is not really possible to speak of operational capability. The protection systems for these aircraft are being either evaluated or studied. The "UH-1H" and the "BO-105" can be classified in the first category, whereas the "S-76" and the "365N", although proposed with a complete system of protection against ice, have not to date been submitted to any tests under icing conditions, at least not for the protection of rotors.

The U.S. Army attempted to qualify the UH-1H with a partial ice protection system installed for flight in limited icing conditions. The experimental JUH-1H, with rotor ice protection, was used during tests to determine operational limits of the UH-1H equipped with protection of all necessary components other than the rotor system. The experimental rotor ice protection system was used only to allow the limits of the partial ice protection system to be probed in safety. Insufficient testing was accomplished to define operational limits.

In the case of the BO-105, the operational limit of the aircraft can be considered as related to the suppression of the off-time in the deicing cycle of the main rotor blades. The limit is reached for an outside temperature of -20°C . It is not yet possible to describe a workload for the crew since the designs are not frozen.

Design requirements for the UH-60A, YUH-64A, and CH-47D include a capability for continuous flight in "moderate" icing conditions. Moderate icing is defined as an ice accumulation of 1/2 inch (1.27 cm) on a small probe in 20 miles (37.2 km). This definition results in an implied limit of 0.45 gm/m^3 liquid water content (average over the period of time). Ice protection systems incorporated on these helicopters are expected to be adequate in icing conditions of up to 1.0 gm/m^3 at temperatures as low as -20°C .

The UH-60A does not yet have an operational release for flight in icing conditions; however, the U.S. Army expects to have sufficient test data by the end for the 1980/1981 winter test season to provide a release.

The YAH-64A ice protection system is scheduled to undergo initial development tests during the 1980/1981 icing test season.

The CH-47D prototype helicopter is equipped with rotor ice protection; however, the U.S. Army is attempting to define the operational capabilities and limitations of the CH-47D without rotor ice protection as well as with rotor ice protection. Test data is not yet sufficient to define these operational limits.

4.6.4 Operational Aircraft

For several years, a few aircraft have been able to fly and operate in an icing atmosphere. Those aircraft can be classified into two categories:

- non-protected main and tail rotors,
- ice protected main and tail rotors.

The operational envelope varies widely from one aircraft to another. The non-protected aircraft have a restricted flight envelope in icing conditions, whereas those fitted with protected rotors are the prototypes of the "all-weather" aircraft of tomorrow. The quality, the reliability, and the redundancy of protection systems have a large share in the operational character of these aircraft; two examples are discussed below:

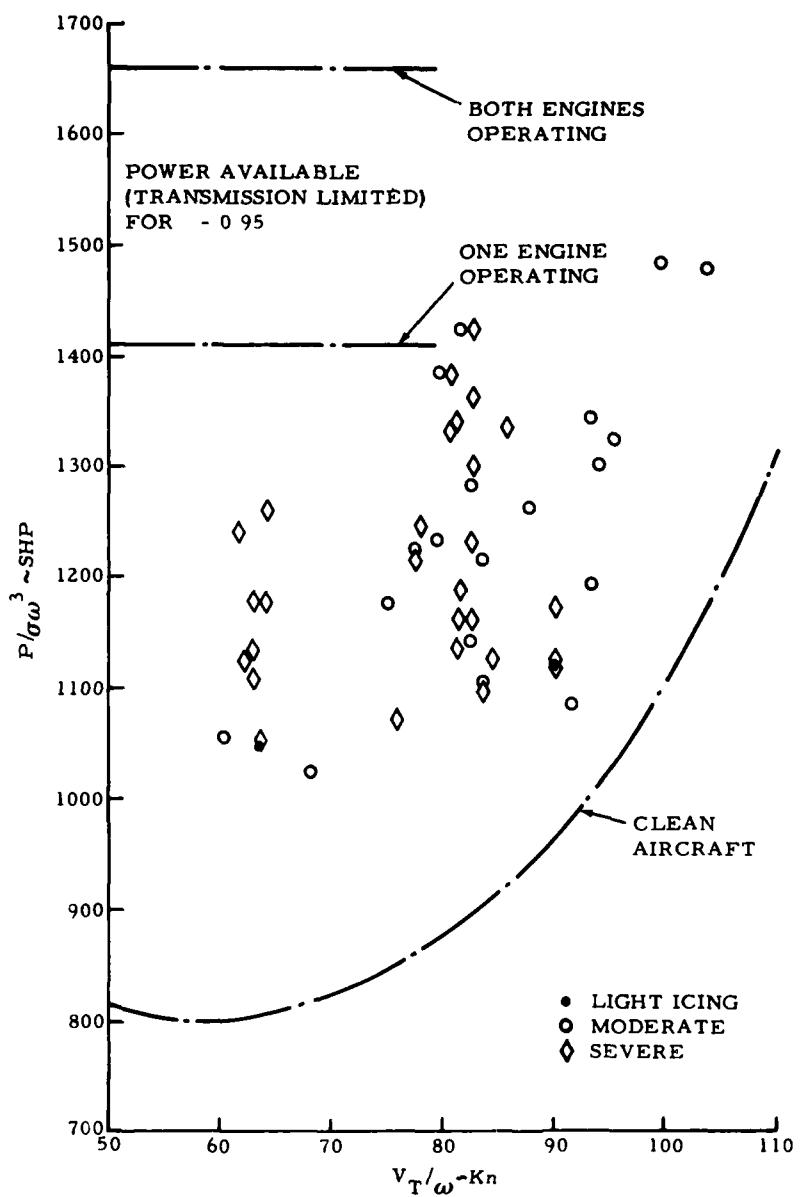


FIGURE 4-44. POWER REQUIREMENTS IN ICING, WESSEX 5

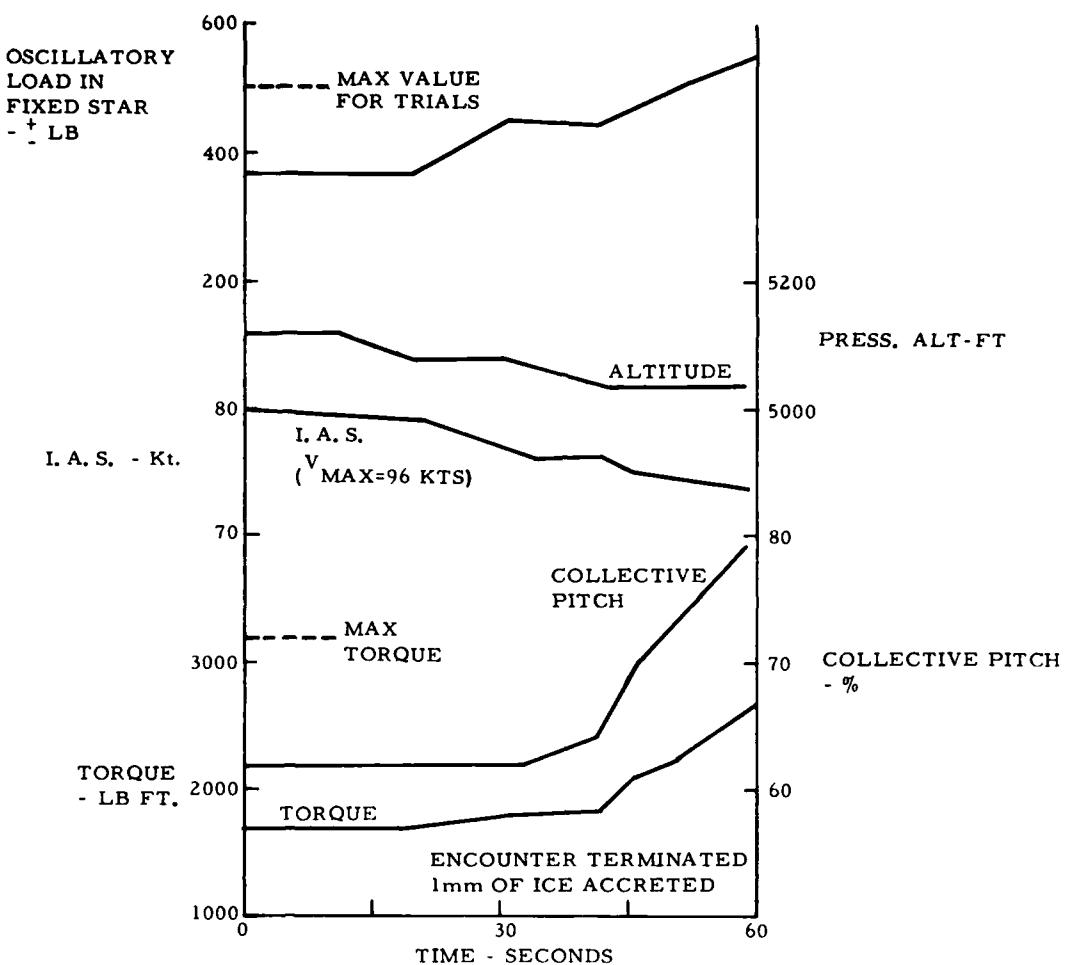


FIGURE 4-45. RAPID ONSET OF ROTOR ICING O.A.T. -3.5° C - WESSEX 5

TABLE 4-7. UH-1H AUTOROTATIONAL CHARACTERISTICS

Icing Exposure (minutes)	Static Temperature	Visual Probe Ice Thickness (inches)	Torque Increase (percent)	Rotor Speed (rpm)	
				No Ice	Ice
17	- 5, 5	3/16	3	310	304
21	- 4, 5	1/4	12	303	293
45	- 5, 5	3/4	10	300	285

Note: No ice and ice rotor speed compared at identical density altitudes

CH 124

The main and tail rotor blades of this aircraft are protected by electric heating strips, and the flight envelope is naturally fairly large. At the present time, the aircraft is authorized to fly in continuous maximum icing conditions at ambient temperatures down to -10°C . The aircraft performance characteristics are not available, but it would be necessary to assess the effect on performance of the change in the blade profile caused by the heating mats (increase in blade airfoil drag).

Crew workload is probably reduced by the automatic heating cycle control (including cut-out periods) linked to the temperature indicator.

This aircraft has a good degree of protection, but relatively little operational experience. This is due to the fact that this protection is considered more as an emergency system than an operational system, despite its own emergency mode feature.

PUMA

The experimental work and development of the protection systems was done with 232 hours of flying time, during which the deicing equipment was operated for about 150 hours (in three annual campaigns). This experience is being complemented by a current evaluation exercise being carried out on three PUMAs by the French Army.

All the PUMA ice protection systems were designed to meet the icing condition specifications contained in FAR 25, Appendix C. The helicopter's flight envelope is not affected by potential or actual icing conditions. In addition, the PUMA's protection has been extended to other phenomena associated with icing conditions, such as lightning, gusting, and hail.

Special attention has been paid to improving system "reliability"; for example, as with the CH 124, the heating mat control, supply distribution and monitoring electronics have been duplicated so as to provide redundancy.

Loss of performance is mainly due to the multipurpose air intakes. Range is reduced by 2 percent when these intakes are open, and by 5 percent when they are closed; hover performance is not affected. As for category A performance levels in climb, these are identical to those of the basic aircraft with a weight supplement of:

- 350 kg with the bullets closed,
- 150 kg with the bullets open.

In severe icing conditions, the equivalent performance levels are those of the basic aircraft at instantaneous weight conditions increased by 500 kg. This fictitious weight supplement corresponds to the performance loss due to the air intakes and to the aerodynamic efficiency loss in the fuselage (figure 4-46). Using figure 4-47, it is possible to calculate the available power reserve up to 10,000 ft (3,049 m) in altitude and at temperatures between 0° and -10°C .

The flight manual indicates no flight limitation in snow or freezing rain.

4.6.5 Operational Capability Improvements of Existing Helicopters

In order to improve the operational capability of helicopters, they must either be made capable of flying in all icing conditions (i.e., there should be no reduction in the aircraft's usual altitude/temperature flight envelope, due to the presence of ice), or else equipped with instruments for detecting icing conditions at a distance so that they can be avoided.

It is quite obvious that an aircraft with unprotected rotors will always have a very limited flight envelope in icing conditions (which may, nevertheless, be deemed adequate by some operators). For example, the CH-53 has a limited capability; however, a risk of blade damage is apparent.

The means by which the operational capability of existing helicopters can be improved are therefore as follows:

- installation of ice measurement and detection equipment
- protection of main and tail rotors
- anti-icing system on windscreen
- anti-icing system for air-intakes and engines
- ice protection of other critical components
- lightning protection systems.

4.6.6 Retrofit Potential

Most helicopters include ice protection equipment for the engine bell-mouth, front frame, and pitot tube. Some, in addition, are equipped with anti-iced forward facing windshields. The retrofit of an existing helicopter to incorporate complete ice protection is considered to be feasible but must be determined on an individual basis by analyses such as cost benefit trade-offs.

The approach envisioned for retrofit of an existing helicopter would include determining through analyses and tests which components must be protected. Based upon current experience, most helicopters will require protection of main and tail rotor blades (or other anti-torque devices), windscreen, pitot and static sensors, critical control

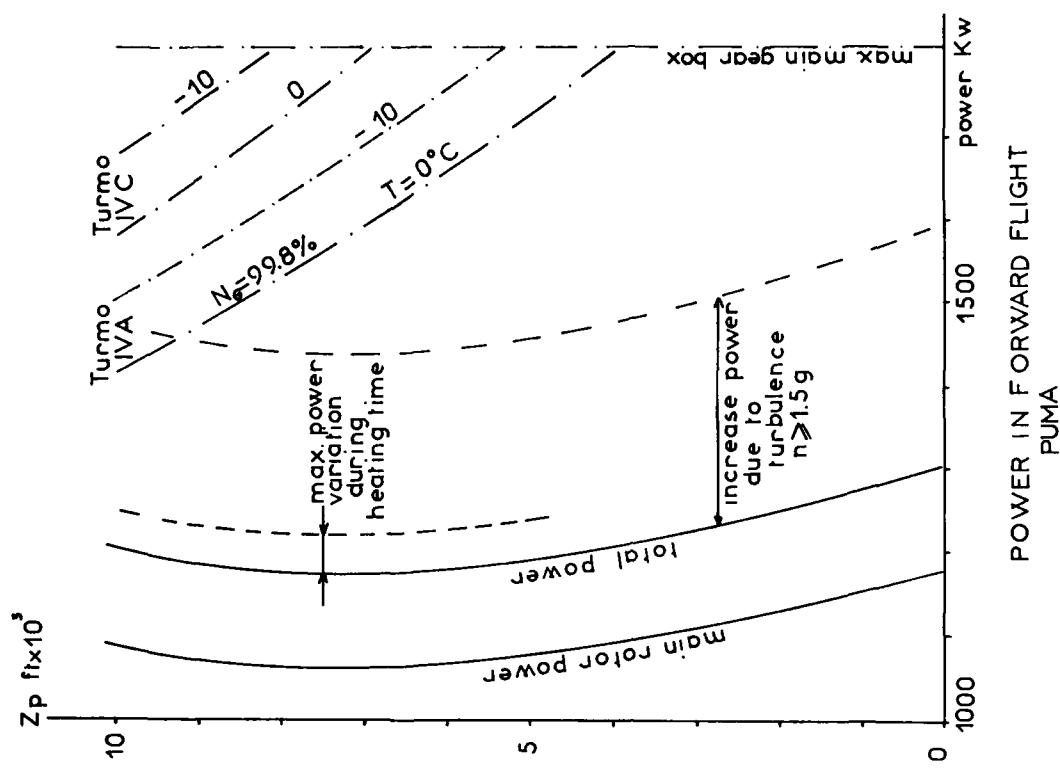


FIGURE 4-47. PUMA: POWER IN FORWARD FLIGHT

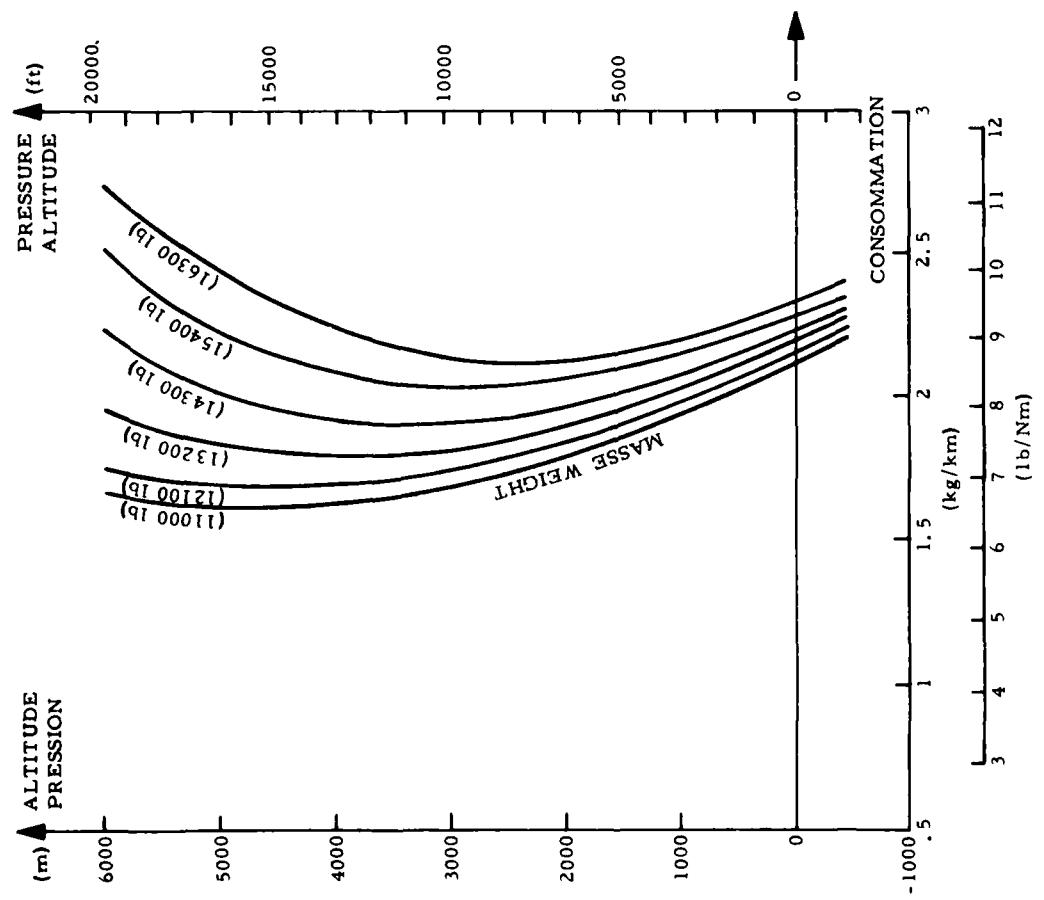


FIGURE 4-46. PUMA: SPECIFIC FUEL CONSUMPTION IN CRUISE (2 ENGINES OPERATING)

surfaces, armament equipment, and ice detection devices.

Retrofit of ice protection systems is always possible. The aircraft down-time for this operation will depend on the number and complexity of the systems involved.

The most complicated part of the operation is the rotor anti-icing or deicing system, which requires the installation of slip-ring distributors, wiring looms, the integration of control and indication electronic systems, etc. On the PUMA, for example, complete icing protection retrofit requires no less than about 30 modifications, for which the aircraft has to be returned to the manufacturer's workshop.

The U.S. Army concept for new helicopter development programs (UH-60A and AAH) is to fit each helicopter with minimum equipment necessary to accept an ice protection kit. For example, the YUH-64A transmission is designed with a standpipe in the transmission to accept the slip-ring and wiring harness assembly for rotor ice protection. All rotor blades will contain the electrothermal heater mats. Ice protection kits can be installed by the manufacturer on selected serial number helicopters or added, as the need arises, in well equipped maintenance depots. The Canadian Forces incorporated ice protection systems during retrofit of their entire fleet of CH-124 helicopters. This was accomplished by the manufacturer, in conjunction with other product improvement programs.

4.7 CONCLUSIONS AND RECOMMENDATIONS

This section includes a discussion of research or development work deemed necessary to be conducted to advance the state-of-the-art of helicopter ice protection systems. Emphasis is placed upon advanced concepts of ice protection that show promise of cost effectiveness, lightweight, low-power requirements, and improvements in reliability, maintainability, and detectability.

4.7.1 Helicopter Rotor Blade Ice Protection

Sections 4.1 through 4.4 of this report discuss the various concepts of rotor blade ice protection in use today or conceived as having potential application to helicopter rotor blades. The cyclic-electrothermal deicing concept is considered the only viable concept for application to rotor blades in the near future. The penalties attendant with this concept are considered excessive (weight and cost). There is an identified need for development of advanced concepts. The advanced concepts recommended for further R&D are listed as follows:

- a. Ice Phobic coatings
- b. Vibratory
- c. Pneumatic
- d. Microwave
- e. Hybrid
- f. Freezing Point Depressant

Flight testing conducted to date by various Government agencies for research, development, qualification, or certification purposes has, for the most part, been limited to supercooled cloud and snow conditions. From these tests, it can be concluded that snow conditions (alone) present little hazard to helicopter rotor blades unlike icing and ice shedding phenomena associated with supercooled cloud, mixed, and freezing rain conditions. It is recommended that concerted efforts be initiated to quantify and understand the phenomena of ice accretion and ice shedding as they relate to the various ice protection concepts in these various environments. These efforts should include, in addition to those recommended in section 2:

- a. Icing tunnel tests
- b. Ground based and airborne simulated icing tests
- c. Incorporation of research related objectives in ongoing or planned tests (development, qualification, or certification) as a means of acquiring needed test data.

Flight testing conducted to date, by various Government agencies, has been accomplished with various test techniques and various test instrumentation. Little attention has been given to quantification of performance degradation, which is primarily a function of helicopter rotor blade geometry, ice shapes, and ice thickness. It is recommended that concerted efforts be made during flight test efforts to quantify the effects of ice shapes and ice thickness on rotor system and helicopter aerodynamic performance.

Little data are available on rotor ice protection cost, reliability, and maintainability for concept comparison purposes. It is recommended that, during future research, development, and design efforts as well as operational efforts, concerted efforts be made to document these data.

Rotor blade aerodynamic performance and dynamic characteristics are affected by the presence of ice. To minimize these effects, ice protection devices must be controlled in a precise manner. It is recommended that concerted efforts be established to develop rotor ice protection control system concepts.

4.7.2 Ice Protection of Other Helicopter Components

Section 4.5 of this report discusses ice protection technology of other helicopter components. It is concluded that, unlike rotor blade ice protection, technology for protection of other components is basically in hand as a result of continual developments for application to fixed-wing aircraft. Only slight differences exist between ice protection of fixed-wing and helicopter components. These include:

a. Engine Inlets - Helicopter engine inlets typically include inlet separators, barrier screens, or deflectors to preclude entry of potential foreign object damage material (FOD). Fixed-wing aircraft do not typically include devices of this type. Consequently, ice protection of helicopter engine inlets has presented a unique challenge to researchers and developers of new helicopters. The result is a myriad of complicated, heavy, and in some cases, "ugly" devices that, in most instances, perform the required function. It appears that the T-700 engine and its unique, centrifugal inlet particle separator meets the need with minimal complexity. The reason this engine meets the need is concerted efforts on the part of the US Army during the engine development phase to address the entire issue of FOD and inlet icing while the engine was being developed specifically for helicopter applications.

It is recommended that future engine development programs consider the engine/engine inlet interface from the outset to include the entire issue of FOD and inlet icing. In addition, various concepts of ice protection such as the electroimpulse concept show promise for application to engine inlets. Specific efforts to further investigate and develop these applications is recommended.

b. Weapon Subsystems - Modern attack helicopters, such as the US Army Advanced Attack Helicopter, rely upon a large variety of weaponry that must be functional and accurate after exposure to icing conditions. Most of these weapons are externally mounted and exposed. Similar weapons on fixed-wing aircraft, for the most part, have not been ice protected. Critical weapons were stowed (closed breech or doors) or ice protection relied upon high Mach number heating. Consequently, armament subsystem ice protection technology lags that of other subsystem components.

It is recommended that concerted efforts be established to develop an array of simple ice protection devices for application to helicopter armament subsystems.

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5. PROPOSED STANDARD REQUIREMENTS AND PROCEDURES FOR ICING CLEARANCE5.1 INTRODUCTION

This text proposes basic clearance requirements for certification of the helicopter to fly safely in icing and snow conditions and to provide guidance on design, test program and certification. Other means of compliance may be equally acceptable if they are approved by the certification authority. As recommended at the Cleveland Workshop (ref 4-14) in July 1978 this text could apply to both military and civil helicopters. But, because there are still uncertainties associated with helicopter flight in icing, the rigour with which the requirements and procedures included here are applied will govern the degree of risk inherent in the subsequent clearances, and the acceptable level of risk may vary between civil and military helicopters.

5.1.1 Basic Hypotheses

- Icing Atmosphere. The icing atmosphere is at present defined in the FAR 25 Appendix C.* It has given very useful parameters for the design of icing protection systems for aircraft. Taking into account the measurements obtained with new, sophisticated instrumentation, this atmosphere appears to be questionable, but, for lack of up to date data, it is proposed that FAR 25 APP.C be used as the general basis for helicopter design and certification requirements for the time being.

- Operational Icing Envelope. The operational icing envelope is that portion of the FAR 25 APP.C envelope within which the helicopter will be cleared to operate. This envelope may be the whole helicopter flight envelope or only a part of it. The manufacturer or user must ask for a clearance to fly in the defined operational icing envelope.

5.1.2 General Standard Requirements for Helicopters

(a) If certification for flight in icing conditions is desired, the operational icing envelope shall be defined to the certification authority and applicable paragraphs of this document must be demonstrated. Either full or limited certification may be applied for.

(b) The helicopter must be able to operate safely in the continuous and intermittent icing conditions defined by FAR 25 Appendix C as prescribed in paragraph 5.1.2(a). An analysis must be performed to establish, on the basis of the helicopter's operational needs, the adequacy of the ice protection provisions for the various components of the helicopter.

(c) In addition to the analysis and ground testing, the effectiveness of the ice protection system and its components must be shown by flight tests of the helicopter in measured atmospheric icing conditions. In addition the adequacy of the ice protection system must be determined by one or more of the following tests:

(1) Laboratory clear air or simulated icing tests or a combination of both, of the components or adequate model of the components.

(2) Clear air flight tests of the ice protection system as a whole, or of its individual components.

(3) Flight testing of the helicopter or its components in measured or properly calibrated simulated icing conditions.

(d) As a part of the whole substantiation for full certification, as a minimum, each of the following shall be adequately taken into account:

- engine with its helicopter air intake or, if the intake is separately qualified, engine alone
- rotor systems including droop stops, flap restraints, and external vibration dampers
- flight controls
- necessary probes or sensors: pitot heads, statics, angle of attack, ice accretion, ice detector, etc., and their qualification status
- windshields and wipers
- unprotected surfaces
- all vents and exhaust ports
- emergency access/exit
- antennas, radome
- external stores and systems

* UK use design requirements given in AvP 970, Vol 3, Chap. 714 for military helicopters and BCAR D1-2 for civil aircraft. US Army uses design requirements defined in USAAMRDL-TR-75-34A, Vol 1, Fig 12, for military. Hence in this document a reference to FAR 25 APP.C shall be replaced, for the UK and US Army by their appropriate requirements.

- ice shedding trajectories from the whole helicopter
- minimum instrumentation required for operation within the operational icing envelope (navigation instruments included)
- following natural icing tests, including measurements, an approved extrapolation analysis for the operational icing envelope for which clearance is permissible
- failure analysis and tests
- falling and recirculating snow
- ice crystal, and mixed ice crystal and supercooled water
- freezing fog
- freezing rain
- slush
- safety during embarkation and disembarkation, rotors in rotation
- cleaning the helicopter before take-off when ice or frost formations are present, taking into account the safety of the following flight
- lightning, electromagnetic compatibility
-

5.2 SPECIFIC REQUIREMENTS AND ASSOCIATED RECOMMENDED PROCEDURES FOR ICING CLEARANCE

5.2.1 Requirement for Engine and Helicopter's Air Intake System

Each engine, complete with its air intake systems, duct and icing guard, with all its icing protection systems operating, must operate throughout its flight power range from flight idle to maximum rated power, to include any contingency/emergency power ratings:

- in continuous maximum and intermittent maximum icing conditions of FAR 25 APP.C,
- in snow both falling, blowing and recirculating,
- in ice crystal cloud conditions, freezing fog, freezing rain, slush and mixed crystal and water conditions;

without unacceptable:

- immediate or ultimate reduction of engine performance,
- increase of engine operating temperature,
- deterioration of engine control characteristics, and
- mechanical damage.

5.2.1.1 Recommended Procedures for Icing Clearance for Engine and Air Intake System

The helicopter's air intake system includes: the air intake itself, any duct, guard or specific engine intake-related icing protection device fitted on the helicopter.

In order to obtain an icing clearance the following ground tests are required. Furthermore adequate testing in natural icing with proper instrumentation is required (para 5.1.2(c) refers), for which the use of closed-circuit television (CCTV) or photography is often necessary.

- Especially for helicopters, engine behaviour depends on the ability of the air intake system to protect against ice and/or slush shed from any part of the aircraft. Where appropriate testing facilities are available, it is recommended that testing be conducted on a fully representative engine installation, taking into account the absence of rotor downwash and the various flight attitudes by adjustment of the inflow angle. Separate assessment and/or testing of the intake system and engine are not excluded; in this case the precise details of the tested intake system will be defined in the engine approval documents. It will be finally the responsibility of the helicopter manufacturer (with the concurrence of the engine manufacturer) to show that the engine tests are valid for his particular installation.

- Non-altitude testing is permissible where appropriate substantiation can be presented, but this could involve modifications to the other test conditions of the method and could also necessitate confirmatory tests in natural icing conditions.

- Where ice or slush could enter an engine, tests to determine the amount of ice or slush the engine can tolerate are necessary.

These following alternative methods shall take into account the helicopter's flight envelope:

Method 1 is an arbitrary empirical method based on the French practice for engine and helicopter air intake system icing protection. These tests are conducted in an altitude facility in accordance with Table 5-1. A separate test should be conducted at each temperature condition of Table 5-1, the test being made up of repetitions of the following cycle:

32 km in the conditions of Table 5-1 Column (a) appropriate to the temperature, followed by 5 km in the conditions of Table 5-1 Column (b) appropriate to the temperature, for a duration of 30 minutes (or less if a steady state can be established, or until the engine will no longer operate satisfactorily).

- cruise conditions shall be established to both maximum and minimum helicopter speed for -5°C and -10°C ;
- cruise conditions shall be established at maximum speed for -30°C ;
- take-off power setting test shall be conducted only if clearance for take-off under icing conditions is desired;
- the minimum engine power shall be established for the critical conditions;
- larger droplet sizes available in the test facility shall be investigated to show that test results are not significantly different from those for $20 \mu\text{m}$ droplets;

TABLE 5-1

ENGINE AND INLET ICING TEST CONDITIONS

Ambient air temperature $^{\circ}\text{C}$	Altitude		Liquid Water Content (g/m^3)		mean effective droplet size diameter (μm)
			(a)	(b)	
	m	ft			
- 5	1200	4000	0.7	2.4	
- 10	to	to	0.6	2.2	
- 20			0.3	1.7	20
- 30	4500	15000	0.2	1.0	

- The combination of altitude and temperature to be tested will be agreed for each installation;
- Due to the diversity of helicopter air intake ice protection systems, the test program shall be adapted to take account of particular features of engine, engine intake and protection systems to be tested;
- During or at the end of some tests it will be useful to examine the possible ice accretion on and behind the air intake or on the engine;
- At the conclusion of each test the engine should be run up to the maximum power conditions for a sufficient period during which the air temperature should be raised above 0°C to ensure that all ice has shed;
- A test should be conducted for a duration of 30 minutes, with the engine set to the minimum ground idle conditions approved for use in icing, in an atmosphere of -2°C and a liquid water concentration of $0.3 \text{ g}/\text{m}^3$. The mean effective droplet size for the test should be $20 \mu\text{m}$. At the end of the period, the engine should be accelerated to Maximum Take-off Power (in a manner approved for inclusion in the operating instructions) without suffering unacceptable damage or power loss.

Method 2 is the US practice based on their own experience of the Military Specifications' named Conditions 1-2-3 (see advisory circular AC20-73 dated 21 April 1971, pages 26-27).

(a) The engine should be capable of operating acceptably under the meteorological conditions of Appendix C of FAR 25 over the engine operating envelope and under conditions of ground fog.

(b) Experience has indicated that testing to the points set forth in the following table and schedule has been considered a successful means of showing compliance if used in conjunction with the critical conditions determined in the design analysis:

TABLE 5-2
ENGINE AND INLET TEST CONDITIONS

Icing Condition	1	2	3
Liquid Water Content, g/m^3	2.	1.	2.
Atmospheric temperature, $^{\circ}\text{C}$	-5	-20	-1
Mean effective water droplet diameter, microns	25.	15.	40. minimum

(1) Operate the engine steadily under icing conditions 1 and 2 for at least 10 minutes each at take off setting, 75 percent and 50 percent of maximum continuous power and at flight idle setting, then accelerate from flight idle to take off. If ice is still building up at the end of 10 minutes, continue running until the ice begins to shed or until the engine will no longer operate satisfactorily.

(2) Operate steadily at ground idle setting for at least 30 minutes under icing condition 3 followed by acceleration to take off setting.

(3) While at cruise and flight idle, for engines with icing protection systems, operate for at least one minute in the icing atmosphere prior to turning on the icing protection system.

(c) Engine operation in these icing conditions should be reliable, uninterrupted, without any significant adverse effects, and should include the ability to continue in operation and to accelerate. Some power reduction is acceptable at idle power settings but all other operation should be unaffected.

(d) Special consideration and tests should be conducted to adequately substantiate:

(1) Engines with inlet screens
(2) Engines with air passages which might accumulate snow or ice due to restrictions or contours.

(3) Unprotected surfaces upon which ice may build up significantly during exposures longer than specified above.

5.2.2 Requirement for Rotor Systems

The general requirement is given in paragraph 5.1.2 of this chapter derived from that for fixed-wing aircraft.

5.2.2.1 Recommended Procedures for Icing Clearance of Rotor Systems

At the present time, all certifying authorities require testing in natural atmospheric conditions.

The icing clearance shall be based on the test results obtained in natural icing conditions with a properly instrumented test helicopter. Supplementary substantiation from analysis, ground tests and simulated in-flight or wind tunnel icing tests may be useful in evaluating the amount of natural icing testing required and in assisting in extrapolation of natural icing test results.

The overall level of safety during flight in icing shall be acceptable taking into account any failures which may occur, including those of ice protection systems.

A. Instrumentation

The following instrumentation will be required for acquisition of rotor systems icing clearance data, taking into account that deficiencies are likely to give an inadequate understanding of the behaviour in icing and thus make extrapolation hazardous, extend the testing necessary for a given standard of safety in service and prolong the development of the systems:

(a) Cameras fitted in such a manner as to record ice accretion, ice shedding and residual ice.

(b) Instruments to measure Outside Air Temperature (OAT), Liquid Water Content (LWC), droplet size, ice accretion rate and, when available, solid particle content.

(c) Rotor torque and stresses, and airframe vibration levels.

(d) The appropriate performance and characteristics of the rotor icing protection system (if provided), both in icing and in clear air.

(e) Flight test instrumentation to measure helicopter performance and flying qualities parameters.

B. Test Scope

In order to achieve full clearance, tests must be performed as follows:

(a) throughout the minimum required temperature range of 0°C to -20°C, but any opportunity to investigate lower temperatures should be taken.

(b) over the altitude range for which clearance is required.

(c) as far as practicable for liquid water contents specified by the continuous and intermittent maximum conditions for FAR 25 APP.C (without application of the attenuation factor);

(d) for: - protected rotors, in any configuration or conditions, to establish the effect of failure or partial failure of the protection system, or the

accumulation of run-back ice.

- unprotected rotors, in any conditions such as partial or asymmetric shedding, which could degrade the handling, performance and vibration level of the helicopter or its engine(s).

(e) when rotor systems are designed to function under snow conditions, test must be made in snow with the heating on in order to see if any problems may occur when flying in snow conditions.

C. Qualification Criteria

- Protected and unprotected components of the rotor systems shall function properly throughout the operational icing envelope.

- Icing conditions shall not induce excessive pilot workload, unacceptable helicopter vibration, blockage of vents/exhaust ports, improper functioning of rotor droop stops/flap restraint systems, or physical damage due to shed ice.

- After failure of any one portion of the ice protection system, the level of safety shall remain acceptable for continued operation in icing conditions.

- Stress levels of the rotor system and other critical dynamic components during flight in icing conditions shall not unacceptably reduce the fatigue lives established for non-icing flight. Retirement lives shall include appropriate reduction for operation in icing conditions.

- Torque increases and fluctuations (during ice shedding) shall not exceed limits established for maximum torque and torsional stability of the drive system and shall not unacceptably impair helicopter performance. Rotor speed control within normal operating limits shall be possible during ice shedding or accumulation under autorotational conditions.

- Analysis of test data obtained in natural icing conditions, together with any other test data which is valid, and accepted analytical methods may be used to extend the temperature range of the clearance below -20°C and the values of LWC above those encountered and to allow for other conditions which cannot be covered adequately by natural icing testing at this time.

The resulting clearance may then be limited compared with that which is desired. Further extrapolation is permissible only if the degree of risk involved is determined and accepted.

D. Simulated Icing Tests

Method 1. At the present time no test method with existing icing simulation facilities is satisfactory enough to give the basic substantiation that can be obtained for fixed-wing aircraft elements. When artificial icing tests are envisaged, the French propose the following test programme:

(a) Tests in continuous maximum conditions for a period of 30 minutes duration at each of the conditions specified in the following table:

TABLE 5-3
CONTINUOUS ICING TEST CONDITIONS

Atmospheric Temperature ($^{\circ}\text{C}$)	L.W.C. (g/m^3)	Mean effective drop diameter (μm)
- 5	0.7	
- 10	0.6	
- 20	0.3	
- 30	0.2	20

- At the end of the tests any residual ice shall be shown to be acceptable.

- The duration of the above tests can be reduced if it can be demonstrated that the surface is completely ice-free or that self-shedding is repetitive naturally or enforced by cyclic operation of the protective system. However, at least one of the test conditions shall be investigated for a longer period in order to evaluate the margins of the system.

(b) Tests in intermittent maximum conditions. The following conditions must be considered. Above 1200 m intermittent conditions exist. The icing encounters considered include 3 clouds of 5 km horizontal extent with intermittent maximum concentrations as in Table 5-4 separated by spaces of clear air of 5 km.

TABLE 5-4
INTERMITTENT MAXIMUM ICING TEST CONDITIONS

Atmospheric Temperature (°C)	L.W.C. (g/m ³)	Mean effective drop diameter (μm)
- 5	2.4	
- 10	2.2	
- 20	1.7	
- 30	1.0	20

Note 1. When the above tests (a) and (b) are conducted in non-altitude conditions, appropriate justification or amended program test conditions can be presented for approval.

Note 2. When considering simulated icing tests, the flight conditions selected for testing at each temperature should be the most critical, taking into account the operational icing envelope requested by the applicant.

Method 2. The US Army has developed a Helicopter Icing Spray System (HISS) which is capable of producing a simulated icing cloud which approximates to limited natural icing conditions. The HISS can reasonably duplicate LWCs up to 1 g/m³ with a mean effective water droplet size of 28 microns, at temperature down to -20° and pressure altitude up to 10,000 ft. The capability is limited by the size of the cloud and the droplet size distribution. It has been of considerable value for development and airworthiness substantiation purposes but it cannot presently be considered alone for the purposes of certification.

The icing testing is conducted to fill the following range of conditions, each for a 30-minute duration.

Temperature (°C)	Liquid Water Content g/m ³			
	.25	0.50	.75	1.0
-5	X	X	X	X
-10	X	X	X	X
-15	X	X	X	X
-20	X	X	X	X

In the event the helicopter cannot be completely immersed in the cloud, reimmersion will be performed in order that each part of the aircraft will have experienced the 30-minute required exposure time at each condition. The liquid water content will be mechanically regulated based on the current calibration of the spray system. Temperature will be selected from the available atmosphere in the range from 1500 ft above ground level to 10,000 ft pressure altitude and any altitude at which the desired temperature exists.

will be accepted. The cloud dimensions are approximately 8 feet vertical and 32 feet in width.

5.2.3 Requirement for Necessary Probes

- Each airspeed indicator system must have an ice-protected pitot tube or an equivalent means of preventing malfunction due to icing.
- Each static port must be designed and located in such a manner that the static pressure system performance is not impaired by icing or by liquid water running and re-freezing.

5.2.3.1 Recommended Procedures for Icing Clearance of Probes

- Tests could be derived from the MIL-P-83206B.
- Deicing and anti-icing: The tube shall be tested in an icing wind tunnel at an indicated airspeed of 200 ± 25 knots and ambient temperature of $-30^\circ \pm 50^\circ\text{C}$. The water droplet size shall be regulated to provide a liquid water content of 1.25 ± 0.15 grams per cubic meter. Test runs shall be made at angles of attack of 0° and 20° . The procedure for each test run shall be as follows: Ice shall be allowed to form on the tube until either the pitot pressure opening has been sealed or the ice cap has extended 0.50 inch in front of the tube tip. Power shall then be applied to the heater(s) at rated voltage. The total time required to achieve correct pressure readings shall not exceed 1 minute and to remove all accumulated ice shall not exceed 1 minute 30 seconds. The icing test shall be continued for 15 minutes after the ice cap is removed and no ice shall collect on the tube that will affect the pressure measurement.

- If these previous tests are conducted in non-altitude conditions it shall be demonstrated that results remain valid at altitude.

5.2.4 Requirement for Pilot External View

- The helicopter must have a means to maintain a clear portion of the windshield, during the following conditions, sufficient for both pilots to have a sufficiently extensive view along the flight path in the operational flight envelope of the helicopter. This means must be designed to function, without continuous attention on the part of the crew, in:

- heavy and freezing rain
- snow, both falling and recirculating
- in continuous maximum and intermittent maximum icing conditions of FAR 25 APP.C within the helicopter's operational icing envelope;
- mixed icing conditions.

5.2.4.1 Recommended Guidance for Windshield Anti-Icing Heating

- For windshields protected by electrical heating, the following table could be adequate for design purposes (MIL-T-5842A);

TABLE 5-5
WINDSHIELD ICING TEST REQUIREMENTS

Normal cruise speed		Heat requirement w/m ²
Kt	Kmh	
100	185	3800
150	278	5800
200	370	6000
250	463	6300

Note: this heat requirement gives generally an exterior windshield temperature not less than $+2^\circ\text{C}$.

5.2.5 Unprotected Surfaces

- Where ice can accrete on unprotected parts it should be established that such ice will not critically affect the characteristics of the helicopter as regards safety (e.g. flight, structure, flutter...) and shall not unacceptably degrade handling. The subsequent operation of retractable devices shall be demonstrated.

- As an indication from fixed-wing aircraft service experience, the amount of ice on the most critical unprotected main airfoil surface need not exceed a pinnacle height of 75 mm (3 in) in a plane in the direction of flight. In the absence of an acceptable analysis a uniform pinnacle height of 75 mm could be assumed, or any other maximum ice accretion height agreed by the certification authority.

- The critical ice shape on unprotected parts will normally occur during the cruise at a total temperature near 0°C.

5.2.6 Ice Shedding Trajectories from the Whole Helicopter

Ice shedding trajectories from protected or unprotected parts of the whole helicopter throughout the flight envelope should be analysed. If such shedding could interfere with the continuous safe operation of the helicopter, it would be required to demonstrate that the trajectories of such ice are not critical. Furthermore consideration must be given to minimising the risk of ice shed from the helicopter causing injury to persons on the ground.

5.2.7 Instruments Required for Operational Flights

A need exists for some instruments or equipment for identifying icing severity within the operational icing envelope for full or limited clearance. Such instruments would be specified by the manufacturer and agreed by the certification authority. Required instruments could be, but not necessarily be limited to:

- OAT
- Ice accretion device
- Ice severity meter
- Weather radar
- Torque meter
- Any suitable instrument which indicates changes in power necessary for flight.

Note: Navigation subsystems such as antennas, radome..., must not be unacceptably impaired by icing.

5.2.8 Tests in Natural Icing Atmospheric Conditions

A. Tests in Icing Conditions

Flight tests of the helicopter in measured natural atmospheric icing conditions are mandatory. At the present time such tests are the main substantiation for certification purposes. The helicopter shall be fully instrumented for each specific component subject to icing, for measurement of icing parameters and for engine parameters. The natural icing tests carried out on the helicopter will be judged for their acceptability by the evaluation of the icing conditions through which the helicopter has flown in relation to the operational icing envelope wanted within the conditions of FAR 25 Appendix C.

B. Tests in Falling and Recirculating Snow

Taking into account the lack of an approved definition, the fact that the horizontal visibility is not necessarily related to snowfall severity, the variability and difficulty in identifying the worst conditions, quite extensive tests are necessary in natural snow to support a snow clearance. The United Kingdom proposes for guidance the following conditions for both falling and recirculating snow:

- Snow content:
 - .continuous falling snow, unlimited distance: 0.8 g/m³
 - .periodic falling snow for 8 km: 1.5 g/m³
 - .recirculating snow: 1.5 g/m³

In testing the relevant snow factors, the following are to be taken into account:

- ambient air temperature including particularly temperatures about 0°C
- the severity of the snow
- the exposure time
- whether the snow is falling or recirculating

Clearance is normally recommended for the temperature range which has been adequately covered by the tests that have been made except that tests at about -8°C are considered to clear all lower temperatures (except for heated surfaces or surfaces wetted by anti-icing fluid). Snow severity and the exposure times which have been experienced during the testing must also be taken into account. Consideration must be given to the possibility of protective screens and other particle separation tubes or deflection devices becoming blocked, or snow/slush concentrations shedding from the airframe into unprotected engine inlets. In the latter case knowledge of how much slush an engine can tolerate is important.

C. Tests in Ice Crystal Conditions

Ice crystal conditions can seldom be measured and their effects on the helicopter are, so far as is known, covered by the testing in snow and some natural icing test

conditions referred to above. However, if such conditions are encountered during flight test they should be investigated.

D. Tests in Freezing Fog, Freezing Rain, Slush, Mixed Ice Crystal and Water

These conditions, which are not defined, shall be evaluated in the natural atmosphere.

5.2.9 Failure Analysis and Tests

Failure analysis of the ice protection system shall be performed to establish the adequacy of the helicopter to fly safely in icing conditions.

Failure cases of any critical protected part shall be evaluated during natural icing atmosphere tests or by an acceptable analysis.

5.2.10 Safety During Embarkation and Disembarkation

Rotors must be completely stopped unless it has been demonstrated that no danger could result from rotors in rotation either after a flight in icing conditions or on the ground if ice can be accreted and shed.

5.2.11 Cleaning the Helicopter Before Take Off when Ice Formations are Present

The helicopter must be completely cleaned before take off when ice or frost formations are present, unless it has been demonstrated that any ice accreted on the blades, the structure and the air intake system of the engine cannot impair the safety of the aircraft during take off and the following flight.

5.2.12 French Proposal, as an Example of a Table of General Conditions to be Tested for an Icing Clearance for Helicopters

The following table gives the complete flight configurations to be demonstrated, for times appropriate to each helicopter, in natural icing and associated conditions. These tests must be performed with regard to:

1 - Temperature Range. The temperature ranges are based on the different effects of icing observed during previous experience.

TABLE 5-6
ICING CLEARANCE TEST CONDITIONS

Conditions	Temperature Ranges	Main Effects
a	0 to -2°C	run back
b	-2 to -5°C	large ice shapes
c	-5 to -10°C	transition range between large and well-stuck ice
d	-10 to -15°C	well-stuck ice
e	-15 to -20°C	cold ice, possibility of insufficient protection power

Any opportunity to fly in icing at temperatures lower than -20°C should be taken.

2 - Altitude Range. The whole altitude range for which clearance is required has to be explored with particular attention to high altitudes at which the flight power margin is reduced.

3 - Liquid Water Content. To demonstrate LWC values as close as possible to the maximum conditions of the defined atmosphere, it is advisable to fly many times in cumulus and strato-cumulus-type clouds.

4 - Helicopter Weight. Due to the fact that gross weight has a great effect on performance, handling qualities and vibration levels, it is important to test different weights in icing conditions, and in particular gross weights close to the maximum.

5 - Night Flights. Several icing flights must be performed at night in order to identify any specific problem, mainly associated with crew judgement and behaviour, which may be different from those of daytime flight.

6 - Configurations to be Demonstrated for helicopter natural icing tests; see Table 5-7.

TABLE 5-7
NATURAL ICING TEST CONFIGURATIONS TO BE DEMONSTRATED

CONFIGURATION	A Icing	B Snow	C Mixed Conditions	D Freezing Rain	E Gust Lightning Hail
N O R M A L	1.1. TAXI + GROUND HOLDING YES 10 + 30mn a b c d e	YES 10 + 15mn a b	NO	YES 15 mn a b	NO
	1.2. HOVERING YES 30 mn OCE a b c d e	YES 30 mn IGE a b	NO	NO	NO
	1.3. LOW SPEED FORWARD FLIGHT NO	YES 30 mn a b c	NO	YES 30 mn a b	NO
	1.4. TAKE-OFF - ACCELERATION YES a b c d	YES a b	NO	YES a b	NO
	1.5. CLIMB YES* a b c d e	YES* a b	YES* b c d e	NO	YES* b c
F L I G H T	LEVEL FLIGHTS 1.6. Terrain following, speed to be determined. YES 1 hour	YES 1 hour	NO	NO	NO
	1.7. Long range cruise YES 1 hour	YES 1 hour	YES 30mn	NO	YES 30 mn
	1.8. Cruise at max collective pitch allowed in icing YES 1 hour a b c d e	NO a b c	YES 10 mn b c d e	NO	YES 30 mn b c
	DESCENT 1.9. Normal YES* a b c d e	YES* a b c	YES* NO b c d e	NO YES* a b	YES* YES* b c
	1.10. High rate YES* a b c d e	NO a b c	NO	YES a b	NO
F A I L U R E	1.11. APPROACH AND SPEED REDUCTION YES with 10mm of ice b c	YES with 6mm of ice a b	NO	YES with 6mm of ice a b	NO
	1.12. GO AROUND WITH LANDING GEAR RETRACTION (IF MOVABLE L.G.) YES with 10mm of ice b c	YES a b	NO	NO	NO
	2.1. ONE ENGINE FAILURE DURING TAKE-OFF YES b c	NO	NO	YES a b	NO
	2.2. ONE ENGINE FAILURE IN CRUISE YES 45 mn b c	NO	YES 10 mn b c	NO	NO
	2.3. ONE ENGINE FAILURE DURING APPROACH YES with 10mm of ice b c	NO	NO	NO	NO
C A S E S	2.4. DELAY FOR ROTOR PROTECTION SYSTEM ENERGIZING YES b c d	NO	YES c d	YES a b	NO
	2.5. ROTORS PROTECTION PARTIAL FAILURE YES b c d	NO	YES c d	YES a b	NO
	2.6. ROTORS PROTECTION TOTAL FAILURE YES b c d	NO	YES c d	YES a b	YES b c

Notes : * Time to be determined for each type of helicopter.
 ↳ Torque limit to be determined prior to or during tests.

Some French and UK experience in flight testing for icing clearance is described in Annex A to this Chapter.

5.3 LIMITATIONS APPROPRIATE TO PARTIAL CLEARANCES FOR FLIGHT IN ICING

5.3.1 Introduction

Partial clearance indicates that there are some restrictions associated with flight in icing. Restrictions may also be imposed for flight in snow and freezing rain but these are not within the scope of this note. Restrictions on flight in icing arise from the effects of the icing environment and may be necessary because:

- (a) there is insufficient evidence to be sure that flight in particular conditions is safe, and/or
- (b) it is known that flight in particular conditions is unsafe.

In principle, partial clearances can be applied to both protected and unprotected rotors. However, main experience to date is with the latter where the US military and UK (including the CAA) have used partial clearances successfully, with an acceptable level of safety, for some years. However, experience is still relatively limited and the degree of risk for new types is not easy to know with certainty. France on the other hand does not consider that partial clearances are practical/safe because

- at present there are no means which, operationally, could provide an early measurement of icing severity,
- the icing severity within a few miles of the helicopter cannot be known so that it might be obliged to experience excessive icing (i.e., more severe than that permitted by the clearance), even during an escape attempt,
- the particularly rapid response of the helicopter to some icing conditions can impair its airworthiness.

Given that particular conditions of the icing atmosphere give rise to unwanted effects on the helicopter, it is therefore in principle possible to avoid problems or potential problems by

- (a) restricting the helicopter to operating in conditions which are known to be safe, or
- (b) establishing the degree of degradation which can be accepted safely in respect of any of the helicopter parameters which may be critical (e.g., speed, stresses, power required) and limit flight accordingly, or
- (c) a combination of (a) and (b) above.

These methods will be discussed in para 5.3.2.

With any of the methods (a) - (b) above the question may arise as to what may happen if a pilot finds himself unable to respect the relevant restriction or if he meets unforeseen difficulties. If such cases are thought sufficiently likely to occur then provision may be made for operations to be allowed only when there is an "escape route" available to the pilot should it be needed. This aspect is discussed in para 5.3.3. Such a restriction might also be used if the risk due to a failure of a protection system was thought to be too high.

Mention is made in para 5.3.4 of the UK "Potential Icing" clearance as being the minimum partial clearance possible, but which it has not always been possible to underwrite safely.

Detailed requirements for certification of helicopters in icing are discussed in Section 5.1 of this report and are broadly applicable to partial clearances taking into account any relaxations which are permissible because of the reduced operational icing envelope and, if appropriate, the time which is spent in icing.

There is unanimity of view as to the detailed requirements for the flight test (or other) experience necessary to support partial clearances, partly because of the wide differences which can exist in the scope of such clearances. Agreement will no doubt emerge as knowledge of the subject improves and as experience from operational usage increases. Some guidance may be found from Annex A to this Chapter (A&AEE requirements) and from Section 5.1.

5.3.2 Methods of Restricting Clearance

5.3.2.1 By Limitations on the Icing Environment. The relevant parameters and their applicability are as follows:

(a) Ambient Temperature. Icing characteristics change significantly with ambient temperature and this parameter must therefore be known by the pilot. It can be measured sufficiently accurately using existing, well proven instruments. For particular operational routes or zones a temperature limitation may be operationally acceptable in that it may cover all or nearly all temperatures encountered. If temperatures lower than the limit are more frequent there may be operational restrictions, but if these are accepted there is little risk of pilots not being able to respect adequately the limitations with normal standards of airmanship and provided weather forecasts are available. Normally a small margin is allowed in constructing the clearance to allow for inadvertent transgressions of the limitations.

(b) LWC. This appears to be the most important measure of icing severity and needs to be available to the pilot if it is to be used as an icing limitation. Ideally the indication should be a near instantaneous value and suitable instruments have yet to be proved operationally although their use is envisaged in the US. Simple hot rods are currently carried but are difficult and inaccurate to use and can only give an average over at best a period of minutes. This is not adequate for all unprotected rotors where very rapid rises in critical parameters can take place from time to time. Inasmuch as LWC can change rapidly, pilots, even if they are provided with accurate information, will have difficulty in always respecting any particular value of LWC particularly if this is

fairly low ("light" icing). Hence for a clearance to be satisfactory in this respect the helicopter must be able to survive encounters with LWCs higher than those nominally cleared. A possible advantage of a good LWC display would be to allow the pilot to see if a change in altitude would allow continuation of flight in lower LWCs. In cases where the clearance depends on the absolute quality of ice accreted an indication of the latter is needed and one possibility is the use of an IRU (integrating rate unit) in conjunction with the basic LWC indicator.

(c) Droplet Size and Solid Particle Content. These are believed to have a secondary but, perhaps, important influence on the shape of ice formations and possibly on rates of accretion, but precise information is lacking. It is possible that variations in one or both of these parameters may account for the differences in rotor icing seen in similar conditions of LWC and ambient temperature. Given the present incomplete state of knowledge it would be of little practical use to display these variables to the pilot and in any case no practical instruments are available. The risk associated with this deficiency in knowledge can be reduced in practice by extended testing in representative operational conditions and/or, if it is necessary, the provision of an "escape route" for the operational pilot.

(d) Altitude. The reduced rotor aerodynamic margins at altitude usually lead, in cruising flight for example, to larger increases of stresses in flying controls, of vibration, etc., than occur at lower altitudes. The pilot of course has an altimeter as standard equipment and the only difficulties that arise in respecting limitations is in terms of limited operational capability and air traffic control.

(e) Weather Radar. Use of suitable weather radar might allow the worst icing conditions to be avoided on many occasions.

5.3.2.2 By Limiting the Effects of Icing on the Helicopter. The following effects have been found and their implications in terms of clearances are considered:

(a) Increases of Power Required. Increases of power required occur largely due to rotor icing and seem in many cases to constitute a reliable indication of impending difficulties. A margin of safety, depending on the characteristics of the particular helicopter, is allowed when deciding at what point the pilot must take action to vacate the potentially dangerous environment. This point is usually specified as that at which a given rise of torque has occurred (compared to the value in clear air) but it may also be useful to lay down a maximum torque, below the normal maximum value, which must not, in any case, be exceeded.

The latter value may be readily respected using the standard torquemeter but it may be difficult to be sure that the pilot will quickly recognize that the limiting torque rise has occurred. A margin for error may be allowed but if this is found unsatisfactory an instrument to indicate torque rise in any condition of flight could be developed. Very limited UK experience to date has not shown a clear need for this device but the matter is still under consideration. If torque is not presented to the pilot, equivalent engine limits could be derived but they would be complicated and pilot workload might be prohibitive in respecting them unless the limitations were simplified with a corresponding loss of capability.

In the main this method is applicable to unprotected rotors although the need to monitor torque rise (due perhaps to runback on the blades) might occur with heated blades particularly during initial Service flying.

(b) Increase of Loading in Blades and Other Rotating Parts. Significant increases in vibratory control loads have occurred without, on occasions, large rises in power required, and vice versa. The levels found during testing have often dictated a reduction in the flight envelope (in terms of maximum speed or perhaps maximum collective pitch, and altitude) which can be safely permitted in Service use to avoid reduced fatigue life of components. The alternative of accepting a lower fatigue life has never been used but is theoretically possible provided other difficulties associated with, for example, retreating blade stall and large increases of power required are tolerable. Although it has never occurred it is conceivable that the only practical way of keeping loads within acceptable limits would be the use of some form of "cruise guide" indicator. The use of such an indicator might also improve the capability of the machine in icing but so far the restrictions in the flight envelope mentioned above have proved acceptable to users. A stress limit would be an additional limitation to be respected rather than replacing, say, a torque limit.

(c) Increases of Subjective Vibration Level. Increases are likely to occur in a rather random manner and particularly with unprotected rotors may be of a transient nature. Thus vibration in itself is not a satisfactory way of expressing an overall limitation but it is prudent to specify in any type of release that action must be taken, by reducing speed or otherwise, if a significant increase of vibration persists.

The increases in vibration referred to above may be unpleasant but are not likely to be catastrophic in the short term. Much more severe vibration has been experienced with unprotected rotors at temperatures below a particular value (which seems to vary from helicopter to helicopter) due to ice shedding asymmetrically from the rotor. Since this could lead to serious consequences a temperature limit is necessary.

(d) Miscellaneous Effects.

(1) Premature retreating blade stall can occur due to rotor icing and will lead initially to increases of stress and vibration. These areas have been discussed in (b) and (c) above. Both effects usually become more severe as altitude increases.

(2) A significant reduction of autorotative capability can occur with iced unprotected rotors. Attempts to correlate the loss of rotor speed in steady autorotative descent with torque rise have not been entirely convincing (the testing necessary is difficult to carry out accurately) but nevertheless limiting torque rise is likely to be the most satisfactory way of ensuring an adequate margin of safety if a total loss of power is experienced. The need to retain an autorotative capability will depend on the acceptability of the additional risk arising from a reduced autorotative capability. This will usually vary considerably between single and multi-engined helicopters.

(3) Other limitations such as time in icing, absolute quantity of ice accreted, type of ice accreted, may be useful to warn of potential difficulties.

5.3.2.3 By a Combination of Limitations. The distinction that has been made between "limiting the environment" and "considering the effect" is somewhat artificial because it has been shown that, at least with the present lack of knowledge and experience, neither on its own would be adequate. For example the only civil limited clearance to date (by CAA for the S-61) makes use of most of the possible means available and also provides for an "escape route," when needed.

Beyond that it is only worth saying that the UK (for Service helicopters) do not regard an LWC limitation as an efficient way of limiting the helicopter (i.e., its potential may be unnecessarily restricted), and that with some machines it might be unsafe, unless supported by a volume of test evidence that would be hard to acquire or if an "escape route" is available during an adequate proving period of Service use. The US military takes a more pragmatic view in which each case is considered on its merits. The French consider that an LWC limitation could be theoretically good enough but that it is impracticable for reasons previously explained.

5.3.3 When are "Escape Routes" Needed in Service Use?

Although not strictly within the scope of this Section, some account of the extent of testing to validate clearances is necessary in order to understand why additional precautions may be needed.

Within current knowledge and instrumentation available it cannot be expected that a practical test programme can be devised which will guarantee that all possible problem areas will be found. In practice, some reasonable attempt must be made to see a good sample of icing conditions over the temperature and altitude range for which clearance is required. It is thought that some 20-30 hours** of flying in effective icing, following a well defined test programme, usually gives a fair spread of test points. On several occasions this experience has been gained in two full winters' work operating from a suitable test site. In the UK view additional testing is not very effective in adding to overall knowledge, but may be needed to investigate particular aspects in greater depth or, of course, where the helicopter's configuration has been changed significantly. It is assumed that the best instrumentation available has been used for this work and it is particularly important that adequate coverage, by TV or otherwise, is provided, where necessary, to monitor engine intakes, and that the use of a rotor head camera is considered.

In considering the results various difficulties often arise. For example, it may not be clear why an unacceptable torque rise occurred when similar test points gave acceptable results. There may also be a lack of evidence at high values of LWC, above, say, the AvP 970 maximum continuous level. Again it may be difficult to be sure that the engines will continue to function in all circumstances. Before contemplating a release the engine questions need to be resolved but for the rest it must be accepted that at present there are bound to be uncertainties and that even if a release can be constructed which excludes all doubtful points (or even if none actually occurred) this will not guarantee that no difficulties will arise in Service use. Thus if Service flying is to be undertaken within a release based on this philosophy either some degree of risk must be accepted or some additional precautions must be taken.

Two precautions have been used to allow the pilot an escape path if difficulties are encountered. These are:

(a) That at all times there must be a layer of, say, 1000 ft of air between the helicopter and the ground which is either above 0°C or is clear. It is assumed that descending through this air at the rates of descents envisaged will allow enough ice to be shed to re-establish more or less normal performance characteristics. The thickness of the layer of warm/clear air necessary will depend on, for example, whether or not one engine may be lost, and/or the maximum rate of increase of power required in the worst icing situation that is being considered.

The need to have a layer of warm/clear air does, of course, detract considerably from the usefulness of the release. In the UK view, if the experience gained by operators during a considerable time in icing shows it to be unnecessary then it could be removed. At the same time, provided that the results obtained from the original testing did not debar it, the scope of the release might be increased in other directions, retaining the escape route in these cases, so that finally, in as many stages as might be thought necessary, the full potential of the helicopter in question in icing would be established.

(b) For operation over land at low level it is considered sufficient that visual contact with the ground is maintained and that the aircraft shall always be able to land, if it should prove necessary, within a short period of time.

** Minimum A&EE requirements, basically formulated some years ago but subject to change as the subject develops, are for interest included in Annex B to this Chapter.

5.3.4 Potential Icing Clearances. This (in UK Service parlance) means that within specified conditions, e.g., OAT, altitude, flight is permitted if icing is forecast but the icing environment must be vacated if ice starts to form on the helicopter. This release only demands that the icing condition can be vacated safely, allowing, say, five minutes in icing from start to finish. It may be the only release possible if testing has been limited, if the rotor is unusually affected by ice, or if other problems exist such as possible engine flame-out due to accreted ice. It might be thought that any helicopter could safely survive this type of encounter, but it is worth noting that A&AEE has not thought it advisable to recommend a potential icing clearance for Wessex because very rapid and large increases of torque have been seen on a number of occasions.

ANNEX A TO CHAPTER 5 - HELICOPTER EXPERIENCE FOR ICING CLEARANCE

A1. PUMA EXPERIENCE FOR ICING CLEARANCE WITHOUT LIMITATION

The study of the PUMA ice protection system started in 1975, following research experience gained on Alouette III and Super Frelon flights since 1964.

The main problem at that time was the danger of burn-outs on the metal blades spars, leading to quick fatigue destruction of the blade. This problem was solved by the improvement of the reliability of the whole protection system (heating mats and electronic) associated with the use of plastic blades.

So the PUMA No. 04 was equipped in March 1975 with:

- polyvalent air intakes
- plastic blades with electric mats on main rotor (deicing)
- metal blades with electric mats on tail rotor (anti-icing)

Then followed:

Summer 1975: Development flights in dry air, stresses and temperature measurement
 flight time : 81 H
 deicing on : 57 H

Winter 75-76: CANADA trials, mainly at the NRC Spray Rig, to determine the heating and rest times
 flight time : 87 H
 deicing on : 39 H
 effective icing (Spray Rig and natural) : 31 H
 Flights in natural icing showed the inadequacy of the rest times adopted at the Spray Rig

Spring 1976: Data flights and natural icing tests in France:
 flight time : 26 H
 deicing on : 2 H 30 mn
 effective natural icing : 1 H

Winter 76-77: Natural icing tests in France:
 flight time : 70 H
 deicing on : 58 H
 effective natural icing : 24 H
 An incident due to static electricity led to some modifications in the electronic control system. This system became duplex.

Winter 77-78: flight time : 115 H
 deicing on : 92 H
 effective natural icing : 15 H

Global experience. By adding these times to many extra hours spent in flight for other different purposes, PUMA 04 experienced between March 1975 and May 1978:

flight time with icing protection installed	:	428 H
flight time with icing protection switched on	:	270 H
flight time in effective icing conditions	:	<u>71 H</u>

Date of the flight icing clearance : April 25, 1978

Since this date the experience gained with four protected PUMAS during winters 78-79 and 79-80 has not given rise to significant problems.

flight time	:	730 H
deicing on	:	233 H
effective natural icing	:	<u>76 H</u>

Total of effective natural icing experience : 147 H

A2. LYNX FLIGHT TESTING FOR LIMITED ICING CLEARANCE

1. The Lynx has unprotected main and tail rotors and each of its two forward-facing engine intakes is unguarded but is fitted with electrically heated anti-icing mats. A heated windscreen is fitted. The Lynx was not designed for flight in icing but it was decided that flight tests should be made in natural icing to see what capability, if any, was available.

2. For the icing testing the aircraft was extensively instrumented including the fitment of a rotor head camera and TV monitoring of engine intakes and certain parts of the fuselage. The best source of LWC information then available was a hot rod device which could be recorded on TV when necessary to improve the estimation of LWC as far as possible. Main rotor stresses were recorded.

3. The first trials were made in Denmark in 1975 -

Period of trials	11 Jan to 7 Mar
Icing tests	31 flights, total flight time 24 hrs
Time in icing	14 hrs
Ambient temperature	0 to -9°C
Altitude	up to 9500 ft

Insufficient experience had been gained to justify a clearance and some small modifications to the fuselage were needed to prevent build up of ice that might shed into the engines.

4. The second set of trials was made, again in Denmark, in 1976 -

Period of trials	10 Feb to 24 Mar
Icing tests	28 flights, total flight time 26 hrs
Time in icing	16 hrs
Ambient temperature	-0.5° to -13°C
Altitude	up to 7000 ft

5. Subsequent to these trials a few hours flying were devoted to establishing the trajectories of simulated ice shedding from the fuselage. After these tests the present limited clearance was issued.

6. Since then service flying has been very limited because of delays in introducing the appropriate modifications but approximately 50 hrs of icing flying (total flight time) has been achieved, within the icing clearance, during tests of external stores, engine intake heater mats, etc, in Canada.

A3. SEA KING FLIGHT TESTING FOR LIMITED ICING CLEARANCE

1. All the trials which have been carried out in icing are summarized in para 2 below. Much of the testing, particularly in the 1977 trial, was primarily aimed at establishing that the several standards of engine protection involved were satisfactory. Tests were made at ambient temperatures down to -15°C and at altitudes of up to 5000 ft.

2. Year	Period of Trials	Location	Spray Rig Tests Hours	Natural Icing Tests	
				Sorties	Hours in Icing
1970	16 Feb-16 Apr	Ottawa	2	2	1
1970-1971	18 Oct-15 Dec 22 Jan-31 Mar	Ottawa	1½	16	7½
1972	12 Jan-18 Feb 2 Mar-24 Mar	Prestwick Gardermoen		3	2
1972-1973	Oct - Mar	Ottawa	2½	12	9½
1974	Jan - Apr	Ottawa	2	9	5½
1977	18 Jan-29 Mar	Ottawa		13	18½
			7 3/4	55	44

3. The clearance for the Sea King also takes into account other agencies' experience of the S-61. Service experience of the Sea King in icing has not been extensive with an estimated total time of some 20 hours.

ANNEX B TO CHAPTER 5 - A&AEE REQUIREMENTS FOR ICING EXPERIENCE
HANDLING QUALITIES AND PERFORMANCE THAT MUST BE DEMONSTRATED FOR AN ICING CLEARANCE TO
BE RECOMMENDED FOR HELICOPTERS

B.1 ICING EXPERIENCE

B.1.1 For an initial release to Service with a lower confidence level than is normally implied in other types of clearance test experience in icing should have been gained in accordance with the following paragraphs:

(a) A certain amount of experience must be gained in each of the following temperature bands down to the lowest temperature for which certification is sought.

0°C	to	- 2°C
- 2°C	to	- 5°C
- 5°C	to	- 10°C
- 10°C	to	- 15°C
- 15°C	to	- 20°C

NOTE: The requirement for below -20°C is not yet finalised.

(b) For an icing clearance to be recommended the test experience gained in each temperature band must meet the following requirements:

(1) A minimum of 1½ hours should have been spent at LWC's in excess of 25% of the continuous maximum value appropriate to the altitude and temperature at which the test is being conducted. (In selecting the appropriate LWC value no alleviation of severity with horizontal extent will be assumed). Two separate flights should contribute at least 30 consecutive minutes each to this total experience (see Note A).

(2) A minimum of 10 consecutive minutes should have been spent in LWC's in excess of 60% of the maximum continuous value appropriate to the altitude and temperature at which the test is being conducted. In any case the maximum pressure altitude justified for certification (in the particular temperature band being considered) will not normally be higher than that at which this test was actually performed. (see Note B).

(c) The maximum altitude certified for flight in icing will normally be the lowest that was justified in any of the temperature bands for which certification is sought. However, alternative proposals will be considered if they can be used safely for the operations proposed for the helicopter (see Note B). Additionally the lowest temperature certificated for flight in icing will be the lowest achieved in the lowest temperature band for which certification is sought.

B.1.2 It is considered that the rules listed in B.1.1 will remain valid whichever set of icing atmosphere requirements are used, i.e., the requirement of FAR part 25 or JAC draft leaflet 714/1.

B.2 HANDLING AND PERFORMANCE CRITERIA

B.2.1 For certification for flight in icing a flight envelope must be defined (in terms of parameters such as speed, collective pitch, altitude, OAT and mass) within which it is estimated, on the basis of the data available, that all manoeuvres appropriate to instrument flight with rotors degraded by ice can be undertaken without unacceptable handling characteristics or excessive vibration occurring. Within this envelope the increase in stress levels under such conditions (if any) shall be such that the fatigue lives of components remain significantly unchanged. (Alternatively some reduction in component lives might be acceptable provided that clear rules could be formulated for logging the accelerated usage arising from flight in icing).

B.2.2 Within this envelope, the data available should indicate that the transmission power ratings will not be exceeded, or alternatively, the pilot should be given a direct indication of power or torque so that he can take action to avoid exceeding the rating.

B.2.3 For helicopters fitted with a rotor protection system a further flight envelope must be defined within which, following partial or total failure of the main and/or tail rotor deicing system, turning and descent manoeuvres appropriate to instrument flight are possible without encountering unacceptable handling or vibration characteristics. This applies following a first failure and such subsequent failures as it may be necessary to consider. It must be possible to maintain height with all engines operating for a time appropriate to the expected operational use of the aircraft without exceeding the maximum continuous transmission or engine power ratings (see Note C).

B.2.4 Within the declared icing flight envelope it must be shown that the engine operation is satisfactory and that the engine protection system will prevent, with an acceptable level of probability, engine damage or flame-out from ice ingestion. The engine response rates achieved in icing must be suitable for the power changes appropriate to instrument flight. In addition to checking satisfactory engine behaviour in each of the temperature bands where airframe icing can be anticipated (see para B.1.1) evidence must be provided that flight in rain and/or cloud at temperatures between 0°C and +10°C does not promote any engine intake icing problems.

B.3 If certain test points give unsatisfactory results, i.e., the specified handling or performance criteria cannot be demonstrated, then it should be possible to construct a flight envelope (in terms of parameters such as speed, collective pitch, OAT, altitude, and mass) for Service use which excludes such points. If unsatisfactory points cannot be so excluded then it is probable that release for flight in icing conditions will not be recommended.

B.4 It is suggested that operators or airworthiness authorities might wish to specify additional criteria to ensure that critical minimum performance requirements (possibly range) or safety requirements (possibly one engine inoperative climb capability) can be met with the deicing systems functioning, in icing conditions up to some specified level of severity.

EXPLANATORY NOTES

A - The objective of specifying the icing experience requirement in this manner reflects the problem of obtaining enough test results at high LWC values during a practicable test period. The proposed requirements are considered to represent the minimum experience which can be accepted in order to underwrite even an 'experimental' release to Service. It must be understood that the users will almost certainly at some time experience conditions more severe than those encountered during the tests and hence a relatively low confidence level must be associated with any release recommendations made.

B - This requirement is intended to ensure that the user is not allowed to fly at higher altitudes than those tested in case rotor profile degradation leads to handling difficulties, arising from premature blade stall. However, if sufficient data exist in other temperature bands to permit a reasonable appreciation of the effects of altitude on the degraded rotor then this will be taken into account when establishing the overall altitude limitation.

C - This requirement has been suggested because the sample size of 'satisfactory' (see para B.3) encounters in each OAT band can be relatively small. Hence, even if this limited testing proves that level flight can be sustained with the system failed, there is still the risk that untested conditions could provoke an involuntary descent. This risk would be considered acceptable if during the test programme it was shown that, in any of the conditions encountered, there was no case in which a failure of the deicing system led to an enforced descent, and if it has also been shown that the standard of reliability of the deicing system is similar to that of other proven electromechanical systems.

6. CONCLUSIONS AND RECOMMENDATIONS

This chapter summarizes the conclusions and recommendations which derive from the body of this report as contained in Chapters 1 through 5, compares them with reported research programs of the member nations, identifies gaps and suggests some possible follow-on activities to fill these gaps. In general, although the Working Group found that much progress has been made in recent years in all aspects of the rotorcraft icing problem, there are discrete requirements for better instrumentation and analytical methodology for much better low altitude meteorological data and forecasting techniques, better simulated icing testing facilities are urgently needed because of the opportunities of finding natural icing conditions at low altitudes, and there is a unique problem associated with the retention on operational status of certain specific facilities which the helicopter community has come to depend upon, but which the Canadian National Research Council can no longer justify supporting for their own requirements.

6.1 SUMMARY OF CONCLUSIONS AND RECOMMENDATIONS

6.1.1 Operational Environment, Meteorological Conditions and Weather Forecasting Conclusion

It was concluded that at this time the meteorological data base is insufficient to develop any more definitive description of the operational icing requirement for NATO theatres than the spectrum assumed for fixed wing aircraft in the U.S.FAA FAR 25, though the success of operations with limited clearance and the difficulties in obtaining natural icing experience with protected rotorcraft suggest that a less stringent requirement for helicopters operating at altitudes below 10,000 ft may soon be possible. The U.S. FAA is undertaking a reappraisal of existing data and there are some opportunities for getting new data in Europe but there does not appear to be any coordinated effort to pull together a refined definition of the icing atmosphere in the NATO theatre at the lower altitudes at which rotorcraft customarily operate. There is also a need to standardize on instrumentation and techniques for acquisition of meteorological data to assure consistent results.

Recommendations

1.1 Correlate existing instrumentation for LWC and droplet size and recommend options for standardization thereof and for data presentation.

1.2 In coordination with the US FAA, develop a data bank of icing occurrences and their horizontal extent in terms of temperature and humidity, liquid water content and water droplet size with altitude accountability; reduce to FAR 25 format.

1.3 Expand to include mixed conditions, snow, and freezing rain.

1.4 Establish whether special meteorological conditions in the NATO Theatre differ significantly from average worldwide conditions.

Conclusion

Forecasting techniques are currently inadequate to allow unrestricted helicopter operations in icing conditions.

1.5 Support the on-going efforts to improve forecasting in terms meaningful to the helicopter icing problem.

1.6 Encourage more coordination among Cloud Physicists, Forecasters and Helicopter Icing Specialists.

6.1.2 Instrumentation and Analytical Technology

Conclusion

While much progress has been made in the development of better instrumentation to measure liquid water content and droplet size, further improvement is still required to provide better and more consistent data for R&D programs and to improve the sensing capability that is required to control deicing equipment in operational aircraft.

Recommendations

Emphasis should be placed on developing the following capabilities:

For Research and Development Programs:

2.1 Improved capability for measuring liquid water content at temperatures close to zero degrees centigrade and at liquid water contents greater than one gram per cubic meter.

2.2 Improved photographic techniques for recording rotor ice accretion and shedding characteristics.

2.3 A capability for measurement of mixed conditions (ice crystal and snow concentration; ice water ratio).

2.4 Low bulk economical equipment for droplet size measurement.

For Operational Use:

2.5 Instrumentation to provide an immediate indication of rotor torque rise in icing conditions.

- 2.6 Instrumentation for remote sensing of icing severity.
- 2.7 Better definition of the operating characteristics and capability of existing icing severity instrumentation.

Conclusion

The available mathematical techniques for the prediction of ice accretion and shedding characteristics are insufficient to adequately support the a priori assessment of design trade-offs and systems optimization, to establish a base for extrapolating data obtained from models to full scale, and to provide sufficient technology to extrapolate full-scale data obtained from simulated tests or tests in moderate conditions to limit conditions.

Recommendations

Analytical studies should:

- 2.8 Establish whether sophisticated wake models, skewed flow considerations and angle of attack dynamic effects are necessary to adequately predict ice accretion characteristics.
- 2.9 Establish the degree to which rotor flapping centrifugal force and blade flexing determine shedding characteristics and develop analytical methods of ice shedding.
- 2.10 Establish effect of airfoil shape and size on ice formation and the tolerance of section characteristics to ice accretion.

6.1.3 Icing Test Facilities

Conclusion

Ice protection systems for rotorcraft are becoming a standard part of every new helicopter, but testing in natural icing conditions becomes extremely expensive and time-consuming because the limited range and altitude capability of helicopters increases the difficulty of finding natural icing conditions. More and better test facilities will be required to support the much higher level of experimental icing work on rotorcraft. Some progress in icing simulation for full-scale tests has been made with the NRC (Ottawa) Spray Rig and the U.S. Army HISS, but both have limitations.

Recommendations

The following facilities should receive high priority attention.

- 3.1 Expand available icing tunnel facilities for testing of components, instrumentation, and truncated full-scale rotors. Programs for the rehabilitation of the NASA Lewis AWT and for improvements to the icing tunnel at Lucas Aerospace, Artington, are specifically endorsed.

- 3.2 Establish a basis for retaining or replacing the small high-speed NRC icing tunnel.

- 3.3 Develop an improved in-flight simulator with proper droplet size, a cloud of at least 80 x 30 feet, and with the capability for 20 minute duration at a liquid water content of three grams per cubic meter and one hour at one gram per cubic meter. It is recognized that this requirement would demand several times the payload of the largest available helicopter, so it is suggested that a fixed wing tanker with deployable/retractable spray rig be considered as an alternate to meeting this requirement with compromised endurance using a helicopter. Reassess future weapon system plans and the experience to date on the HISS to establish the necessary speed requirement for this improved simulator.

- 3.4 Evaluate the HISS concept and its improvement program with the view to the possible development of a European counterpart.

- 3.5 Evaluate the potential for simulation of falling and blowing snow and study the need for an additional facility to simulate ice crystals and mixed conditions.

- 3.6 Conduct comparisons of test results in simulated icing conditions with results obtained in natural icing conditions for the different components of the helicopter in order to validate simulation facilities and test technologies and to establish the degree to which these can be used to complement natural icing testing.

- 3.7 Establish the effect of solar radiation and relative humidity on rotor ice accretion and shedding (i.e., does icing simulation on clear days with low humidity produce totally valid replication of natural icing phenomena?)

- 3.8 Establish whether truncated full-scale rotor test can provide results in existing icing tunnels.

- 3.9 Establish whether scaling laws do or do not allow evaluation of rotor ice phenomena and what the limitation thereof may be; also investigate optimization of electro-thermal deicing systems and heat transfer modeling in model scale.

Conclusion

A significant portion of the rotorcraft community finds that the Ottawa Spray Rig provides a useful capability, which they plan to use, and would wish to use in the future, but in view of the Canadian National Research Council reluctance to continue to

operate it indefinitely, some plan for either an alternate or for equitable support of the existing facility is needed.

Recommendation

3.10 Encourage the Canadian NRC to retain the Ottawa Spray Rig for the time being while conducting a study to establish an optimum long-term solution for an improved or alternative facility.

6.1.4 Ice Protection Systems

Conclusion

While encouraging progress has been made with electrothermal rotor deice systems, they are expensive, demand large electrical power generation capabilities, and are heavy especially if required to have the capability of handling the extreme ice conditions required of FAR 25. Work is therefore still warranted on other options for rotor deicing such as ice phobics, freezing point depressants, pneumatic, vibratory, microwave and hybrid system concepts and on further optimization of electrothermal systems.

Recommendations

The following areas appear to deserve special attention:

4.1 Improved rotor blade design and control technology for optimizing electro-thermal deice systems and other concepts.

4.2 Research on ice phobics, to extend their useful range beyond the current limitations of about -10°C and 0.5 gram per cubic meter and to increase their ability to resist rain erosion.

4.3 Continued investigation of pneumatic boots, especially the erosion problem, maintenance requirements, and performance impact of boot inflation on rotors with modern airfoils.

4.4 Increased attention to aircraft performance effects during deicing concept evaluations to assure development of an understanding of the base mechanism of how each deicing concept performs in all conditions and to assess its impact on performance under all conditions including autorotation.

4.5 Obtain data on performance, costs, reliability and maintainability of competing concepts during development and operational use.

6.1.5 Icing Clearance Procedures

Conclusion

While available meteorological data at the low altitudes at which helicopters operate are insufficient to establish a consensus on final criteria for icing clearance, a procedure built around general acceptance of FAR 25 as a point of departure, but with significant leeway for the substitution of alternate means of showing compliance, appears to be the best basis for interim use. Such an approach is described in Chapter 5. Additional effort is required to determine the capabilities and limitations of current partially protected helicopters and to reach agreement on the application of the proposed approach to partial clearance, inasmuch as the majority of NATO helicopters still have no rotor icing protection.

Recommendations

5.1 The proposed standard requirement and procedure for helicopter icing clearance be adopted by the NATO military community as an interim approach.

5.2 Consideration be given to this proposed procedure for civil helicopter icing clearance purposes.

5.3 A coordinated effort be made to obtain data from operational experience with cleared helicopters to further validate the proposed clearance procedure.

5.4 Carefully controlled test programs on protected helicopters to explore the limits of safe operation with rotor ice protection turned off.

5.5 Investigate further the extension of this procedure for application to partially protected helicopters.

6.2 NATIONAL ICING PROGRAMS

This section summarizes the Rotorcraft Icing IR&D Programs currently planned with a cross reference to the recommendations noted in Section 6.1.

6.2.1 France

Three areas of research have been defined:

- meteorological data collection for the improvement of data bases on icing
- improvement of analytical means for predicting ice accretion and ice

protection of fixed wings
 - elaboration of a certification method for helicopter rotors in icing conditions, by wind tunnel icing tests
 as follows:

	<u>Applicable Recommendation</u>
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Meteorological Data Collection:

(a) Since 1976 there have been several research programs sponsored in France on fundamental atmospheric physics specially dealing with dynamic, thermodynamic and microphysic characteristics of icing and un-icing clouds (stratiforms and cumuliforms). Some measurements in icing clouds have been done and the data are being analyzed and will be published as soon as possible, in a similar form to FAR 25 APP C. These results will include some other characteristics of icing clouds such as droplet size distribution, LWC, and wind distribution in typical clouds. These Research and Development programs will be carried on to increase the diversity and number of icing encounters in the data base for statistical purposes insofar as it will be possible to equip a new test aircraft. 1.2

Calculation Methods, Ice Accretion and Ice Protection of Fixed Wings:

(b) Development of a computer program for determining shapes of ice accretion on an unprotected profile. 2.10
 (c) Preliminary study of the efficiency of a leading edge heat exchanger.
 (d) Validation of the accretion computer program by analysis and correlation of tests performed independently (previous tests and test performed as part of the research of item above). 2.10
 (e) Establishment of a computer program simulating the operation of a leading edge thermal deicing device allowing in particular the prediction of the formation of runback ice behind the protected zones. 4.1
 (f) Validation of the deicing computer program by comparison with tests of aerofoils equipped with leading edge thermal deicing devices in an icing wind tunnel of CEPr, French Engine Test Center. 2.9
 (g) Collection of results of icing and deicing studies on fixed wings.

Development of a Certification Method for Helicopter Rotors in Icing Conditions, by Wind Tunnel Icing Tests:

(h) Critical study of the various methods that could be envisaged for the qualification of rotors in icing conditions. 5.1
 (i) Completion, in an icing wind tunnel at CEPr (Saclay) of icing and deicing tests of limited durations on helicopter blades, fixed and in periodic motion, at various scales. 2.8
 (j) Completion of icing and deicing tests of helicopter rotors in the S1 Modane wind tunnel. These tests will be performed on complete rotors at reduced scale, and possibly on truncated rotors at reduced or full scale. 3.9
 (k) Adapt the accretion and deicing computer program to the specific case of helicopter rotors. 2.9
 (l) Collection of results of icing and deicing tests on helicopter rotors. 4.5

6.2.2 Germany

(a) Meteorological Data
 Analysis of the 16 flights with the BO 105 and 60 flights performed with the DO-28 of DFVLR:
 In detail it is planned to analyze temperature, humidity, LWC, droplet diameter and droplet distribution to improve the knowledge about cloud-physics and the methods of forecasting, and to compare the obtained values with those given in FAR 25. First results of the analysis were published in the proceeding of NATO Panel X Symposium on Rotorcraft Icing, London, Nov 6, 1978. 1.2

Applicable
Recommendation

(b) Civil System Tests Tests with the BK117 are planned, using the same procedure as with BO 105, to study engine icing and rotor icing with and without deicing system, initially in the spray rig in Ottawa and then under natural conditions.	4.1
(c) Military System Tests Analysis of the tests performed with the DO-28 at the military test center. Analysis of the data and tests performed with the BO 105 at the military test center. Icing tests by MBB with an anti-tank version of the BO 105 equipped with a deicing system, commencing 1981.	4.5

6.2.3 Italy

Agusta has no sponsored government research program at present but may in the future. A working group for helicopter icing is being set up now in Agusta to study the following items:

- (a) Instrumentation - Agusta is in contact with Leigh and Rosemount and will contact Clermont-Ferrand University in France about laser nephelometer.
- (b) Deicing System - It is possible that the Agusta 109 Helicopter will be provided with a deicing system. Agusta is considering electro-magnetic pulse system for deicing the engine air intake.
- (c) Tests - Agusta is considering the possibility of testing a standard A-109 in the Ottawa Spray Rig as well as during flight under moderate icing conditions.
- (d) Meteorological Data - Agusta will contact military and government authorities.
- (e) Cooperation with other Countries - The possible targets could be :
1) Common regulations, 2) Cooperation on research program, 3) Development of a European HISS.
- (f) Theoretical Investigation - Agusta has the capability but no time available at present.

6.2.4 Netherlands

Activities are being performed by NLR on contract for other agencies:

- (a) NLR is collecting relevant information in support of the Civil Aviation Authority program to develop a position on whether or not to accept partial clearance for flight in icing condition of helicopters. After 1981, no further work is planned. 5.5
- (b) NLR is representing the Army and Air Force in participating in the NATO AC/225 Rotorcraft Panel X, Icing subgroup. Main activity is now the gathering of "helicopter icing encounter reports" (inadvertent encounters). 5.4
- (c) A very limited budget is available in the next 5 years for continuing Panel X activities and to be able to advise on requirement-formulation for future Army and Air Force helicopters.) 1.4

6.2.5 Norway

No icing research specific to rotorcraft reported.

6.2.6 United Kingdom

The principal rotorcraft icing activities currently underway or planned in the U.K. are:

- (a) Collection of meteorological data on icing clouds (Met. Office, Cloud Physics Department) 1.2
- (b) Improvement in accuracy of icing forecasts (Met. Office, Special Investigations) 1.5
- (c) Improved instrumentation for measurement of icing cloud parameters in instrumented aircraft. (RAE, Engineering Physics) 2.1

	<u>Applicable Recommendation</u>
(d) Improvement in test aircraft instrumentation such as improved photographic methods (A&AEE)	2.2
(e) Assessment of needs for service aircraft instrumentation and development equipment for service aircraft (A&AEE; RAE-EP; RAE Flight Systems)	2.7
(f) Continued development of mathematical models for droplet impingement, ice accretion and thermal analysis (RAE-EP)	2.9
(g) Wind tunnel measurement of changes in airfoil aerodynamic characteristics resulting from simulated ice accretions (RAE-Structures)	2.10
(h) Experimental verification of mathematical models will continue, including further tests of non-rotating blade sections fitted with electrothermal deicing systems and blade surface temperature sensors. The difference in thermal requirements of metal and composite blades will also be studied (RAE-EP/NGTE)	4.1
(i) Wessex metal blades will be fitted with composite material gloves to investigate thermal requirements of composite blades (Westland; RAE-EP; A&AEE)	4.1
(j) Development of anti-icing pastes for rotor blades and paste blocks for antenna is continuing. Experimental investigation into ice adhesion strength to various surfaces has commenced (RAE Materials; Queen Mary College, London)	4.2
(k) Accumulation of experience with the use of existing partial clearance procedures for North Sea Operations -(CAA)	5.5

6.2.7 United States

The principal rotorcraft icing activities currently firmly funded in the U.S. include:

(a) Reexamination of FAR 25 data base for low altitude trends and collation of additional altitude data being acquired by Navy, University of Wyoming, USAF and U.S. Army to update FAR 25 data base. (FAA, NASA & Air Force)	1.1 1.2 5.2
(b) Conduct oscillating 2-dimensional airfoil tests to determine the effect of pitch rate on ice accretion. (NASA)	2.8
(c) Reexamine facilities for rotor icing testing with special attention to the usefulness of the IRT for tests of tail rotors and truncated larger rotors. (NASA & U.S. Army)	3.1
(d) Verify the published icing scaling laws for fixed (as opposed to oscillating or rotating) bodies, using both the NASA IRT and the USAF AEDC high-speed tunnel. (NASA/USAF)	2.10
(e) Determine key non-dimensional groups for scaling ice accretion of both fixed and rotating airfoils from a modern (using "intrinsic reference variables") dimensional analysis of the governing equations for ice accretion. (NASA Grant with U. of Tennessee).	2.9
(f) Development of transient 1-D and 2-D conduction heat transfer codes for analysing electrothermal deicer systems, or other transient systems such as the proposed microwave deicer. The analysis includes conduction heat transfer through multi-layered structures within the airfoil, and heat transfer through the ice layer. These codes go a step beyond the conventional deicer analysis by including melting of the ice cap and water-ice interface. The 1-D numerical model is completed. (NASA Grant with U. of Toledo).	4.1
(g) Development of a theoretical model that will predict the degradation of rotor/propeller performance in icing. Computer codes are being written for water droplet trajectories in flows around rotor blades in hover. Ice build-up shapes will be calculated for rime ice conditions. Using both vortex theory and lifting line theory, the degradation of rotor/propeller performance will be calculated in terms of efficiency, thrust coefficient, and power coefficient. (NASA Grant with Ohio State University).	4.1

	<u>Applicable Recommendation</u>
(h) Develop ice phobic coatings for rotor blades and fixed airfoils with fundamental studies, both analytical and experimental, on the chemistry of ice phobic coatings. Possible materials for basic studies include block co-polymers, self-healing films such as electrolytes in polymers, silicon oils and greases, and coatings which weaken the mechanical strength of the ice near the interface. (USA CRREL and NASA Grant with Clarkson College).	4.2
(i) Development of a microwave ice accretion measurement instrument to see if it can simultaneously detect ice and measure its thickness and accretion rate. (NASA Contract).	2.2
(j) Testing of a freezing point depressant fluid ice protection system that could have possible application to engine inlets or possibly to rotor blades, as well as to fixed wings, antennas, etc. The possibility exists to ooze fluids through porous composite materials as well as through porous stainless steel mesh. (NASA Grant with U. of Kansas).	
(k) Development of a numerical ice accretion modeling code for rime ice, glaze ice and conditions in between. This code forms the starting point in calculating ice accretion for analyzing deicer systems, for calculating aerodynamic performance penalties, and for making artificial ice shapes. (NASA Grant with U. of Dayton)	2.8
(l) Development and publication of water-droplet trajectory codes for flow around 3-D lifting bodies, around 2-D lifting bodies, and flow through axisymmetric inlets at angle of attack (at the mid-plane) and flow through 2-D inlets. A code for 3-D non-lifting bodies has already been published. (Two NASA Contracts)	
(m) Examination of effects of solar radiation and humidity on ice accretion characteristics behind the HISS and in natural icing conditions. (FAA & Army)	3.7
(n) Immediate improvements to the HISS, especially to recapture original cloud size with the improved droplet size. (FAA & U.S. Army)	3.3
(o) Studies to assess methods for, and feasibility of, snow simulation. (FAA)	3.5
(p) Definition of icing test facilities requirements in general and requirements for an optimum in-flight icing simulation system. (FAA)	3.3
(q) Conduct exploratory flight tests of a pneumatic deice system to confirm its performance impact and to demonstrate its ability to shed ice in simulated and natural icing conditions. (NASA)	4.3
(r) Further tests of an ice phobic coating on the UH-1H helicopter rotor in simulated and natural icing conditions. (U.S. Army)	4.2
(s) Limited studies of vibratory and microwave concepts for rotor deicing. (Follow-on to prior work not funded). (U.S. Army)	
(t) Limited controlled exploration of capabilities of the protected UH-1 rotor with deice system turned off to establish capabilities of UH-1's without protection. (Being accomplished as part of ice phobic baseline data). (U.S. Army)	5.4
(u) On-going evaluation of the UH-60 electrothermal deicing systems during flight in icing conditions. (U.S. Army)	5.3
(v) Accumulation of reliability and maintainability data on UH-1 and UH-60 deicing systems. (U.S. Army)	4.5

6.3 ROTORCRAFT ICING R&D COVERAGE ASSESSMENTS

A comparison has been made of the degree to which currently funded plans of the member nations are already addressing the priority needs as defined by this report. Table 6.1 summarises the situation in matrix form, and identifies items which are not clearly addressed by these national programs. These items will be discussed below, with suggestions for opportunities for cooperative effort; item numbers refer to the recommendations of Section 6.1.

TABLE 6-1: R&D COVERAGE ASSESSMENT MATRIX

Recommendations	National Programme	FR	GE	NE	UK	US
		6.2.1	6.2.2	6.2.4	6.2.6	6.2.7
1.1 Correlate instrumentation and recommend standardization					a	
1.2 Develop a data bank of icing occurrences	a	a		a	a	
1.3 <u>Expand to mixed conditions plus snow, freezing rain and fog</u>						
1.4 Establish whether NATO theatre conditions differ significantly			c			
1.5 Improve forecasting capability for icing conditions				b		
1.6 <u>Coordinate meteorologists and helicopter specialists</u>				c		
2.1 Improve capability for measuring liquid water content				c		
2.2 Improve photographic techniques for ice accretion visualization				d	i	
2.3 <u>Develop capability for measurement of mixed conditions</u>						
2.4 <u>Develop low bulk equipment for droplet size measurement</u>						
2.5 Develop instrument for immediate indication of rotor torque rise				e		
2.6 <u>Develop means for remote sensing of icing severity</u>				e		
2.7 Define capability of existing instrumentation				e		
2.8 Clarify modeling requirements for ice accretion prediction	b,i				b,k	
2.9 Establish modeling requirement for shedding prediction	f,k			f	e	
2.10 Establish airfoil shape and size effect on rotor ice accretion	d			g	d	
3.1 Expand available icing tunnel facilities					c	
3.2 <u>Retain or replace NRC icing tunnel</u>					n,p	
3.3 Develop an improved in-flight simulator						
3.4 <u>Evaluate the HISS for European requirements</u>						
3.5 Evaluate potential of blowing snow simulation					o	
3.6 <u>Correlate simulated icing with natural icing</u>						
3.7 Establish solar radiation and humidity effects					m	
3.8 <u>Validate truncated full scale rotor test</u>	j					
3.9 Establish validity of model testing of rotor icing	j					
3.10 <u>Retain or replace Ottawa Spray Rig</u>	e	b		h,i	f,g	
4.1 Optimize electrothermal deice systems	e	b		j	h,r	
4.2 Extend ice phobic research					q	
4.3 Continued investigations of pneumatic boots						
4.4 <u>Establish procedures for deicing concept comparison</u>						
4.5 Obtain performance and reliability/maintainability data on deice systems parameters	l	c			v	
5.1 Adopt proposed interim procedure for military icing clearance	h		a			
5.2 Consider for civil helicopter clearance					a	
5.3 Obtain data from operational experience with cleared helicopters					u	
5.4 Explore the limits of safe operation without rotor ice protection			b		t	
5.5 Investigate extension of interim procedure to partial clearance			b	k		

Items not receiving attention in national programmes are underlined.

1.3 Expand meteorological data base to mixed conditions including snow, and freezing rain: No country reported significant activity in this area nor were any specific suggestions forthcoming on how this complex problem should be approached. It appears that more evidence is needed to indicate whether there are mixed conditions that are more critical than those for which current systems are designed. In all probability, the most effective way to go about this at this time will be to take advantage of the growing body of experience that should become available as rotorcraft with icing protection enter service. Programs in the U.S., U.K., France and Germany in which aircraft are being flown to expand experience on rotorcraft icing should be planned to specifically log any occurrence of mixed conditions and note any evidence of degraded deicing.

1.6 Improve communications between meteorologist and helicopter specialists: The only interagency programs that would appear to touch on this objective are the work related to FAR 25 reassessment in the U.S., and possibly similar work in France and the U.K. It would appear that symposia specifically directed toward bringing these disciplines together might be in order. A workshop to examine criticality, occurrence, and measurement of mixed conditions might be a possible vehicle.

2.3 Develop capability to measure mixed conditions: An extensive program to measure mixed conditions should probably be preceded by more information concerning criticality.

2.4 Development of low bulk equipment for droplet size measurement: No government supported programs were reported. This appears to be a definite gap which should be pursued, probably by the U.K. or the U.S.

2.5 Develop instrument for immediate indication of torque rise: While no specific effort was indicated it is understood that there is an effort on this in the U.K. as part of the ongoing effort to develop better sensors for operational use.

3.2 Retain or replace the NAE icing tunnel: The NAE 1 x 1 foot tunnel has special capabilities to investigate high Mach ice accretion phenomena of airfoils, a capability essential to correlation of accretion models applicable to helicopter outboard sections. It is suggested that NASA take the lead in establishing the options that exist to provide the resources to keep this facility in operation or find an alternative.

3.4 Evaluation of the HISS for European requirements: It was noted that there was no activity in Europe to develop means of simulating icing conditions for full scale testing in spite of the difficulties experienced in finding natural icing conditions for development and clearance tests. The European members were divided on the question of whether a hover spray rig was useful so it does not appear that a European hover spray rig should be built. However, an inflight tanker could well be of interest. It appears that an ad hoc committee to monitor U.S. progress on a HISS and to consider in greater depth a European counterpart is in order.

3.6 Correlate simulated icing with natural icing: While no members reported a specific activity focused on this, a certain amount of correlation is implicit in the programs which include the use of both simulated and natural icing testing in the clearance process. However, it appears that, with the additional experience that is now being obtained with improved droplet size on the HISS and with the expanded experience with the Ottawa spray rig, the time is ripe for a comprehensive review of the whole question in which all icing accretion and shedding characteristics as observed in simulated and natural conditions are methodically examined and some conclusions reached on the degree to which simulated conditions can represent natural icing. While NASA or the U.S. Army would appear to be the logical agencies to do this, maximum advantage should be taken of progress in the U.K. in photographing ice accretion and shedding phenomena.

3.8 Validate truncated full scale rotor tests: Because rotor deicing is often more critical inboard where centrifugal forces are least, a good case can be made for taking advantage of running development tests with truncated rotors that can be accommodated in existing icing tunnels. Opportunities exist to do this with full scale rotors in the FIAT tunnel or possibly even the ONERA S-1 and with tail rotors in the NASA Lewis IRT. However, there is a need to run carefully documented tests to confirm validity of results. The best opportunity to do this might be tests by NASA Lewis, using tail rotors in the IRT. Such work should be prepared as a follow on to current full scale tail rotor tests in the IRT.

3.10 Retain or replace the Ottawa Spray Rig: Although Canada was not an active participant in the Rotorcraft Icing Working Group because of a decision by the NRC to terminate icing research in Canada, the Working Group did undertake a thorough survey of potential users to provide the NRC with a more definitive position on potential utilization of the spray rig. While France and the U.K. had no further plans for its utilization, Italy, Germany and U.S. reported a significant ongoing need. As a result, the NRC advised that plans for a total shutdown of the facility have been postponed for five years. Thus the next five years become critical to establishing plans for replacing this facility, making some arrangements for cosponsored ongoing use or for doing without any low speed icing simulation facility. It is understood that a joint FAA/NASA/DOD icing facility review is being undertaken in the U.S. This issue should be a major agenda item for consideration and it is suggested that Italy and Germany be invited to contribute to deliberation concerning a hover test facility.

4.4 Increased attention to aircraft performance impact during concept evaluations: This recommendation derives from a concern that often little attention has been given in flight test programs of deicing systems to qualifying residual performance degradation as a function of icing severity encountered. No research is required. The recommendation is simply that all flight test program results report on any residual performance degradation as well as on stresses and vibration.

6.4 FOLLOW-ON ACTIVITIES

In the sections above, recommendations for priority R&D on Rotorcraft Icing Research have been made and an assessment of the degree to which unilateral ongoing plans by member nations respond to these is presented. It is hoped that the endorsement of these research efforts by this Working Group will reinforce advocacy for tasks noted, and that identification of gaps in the treatment of priority items will encourage national attacks on these items. However, certain gaps suggest opportunities for follow-on cooperative action. The following further activities which could be sponsored by NATO are therefore suggested:

6.4.1 An AGARD FMP or NATO AC/225 Panel X Sponsored Rotorcraft Icing Workshop to focus on the following specific subjects:

- a) Progress in reassessing FAR 25 icing atmosphere definition and forecasting of icing.
- b) Comparison of results between simulated and natural icing tests.
- c) Operational experience with deicing systems in natural icing conditions, to establish in particular whether mixed conditions including snow, freezing rain and fog produce critical situations demanding definition and design consideration.
- d) Experience with aircraft operating without ice protection under partial clearance procedures.
- e) Controlled tests to probe the limit of capabilities of unprotected helicopters to fly in light to moderate icing conditions.
- f) This workshop could be a place to bring together meteorologists and helicopter engineers. Reports on system experience should address performance degradation as well as loads as a measure of criticality.

6.4.2 An AGARD Rotorcraft Icing Facilities Working Group under Flight Mechanics Panel sponsorship to represent the interests of the European NATO community in discussions of rotorcraft icing research facility acquisition and support and certain other facility related questions. This working group should address in particular:

- a) Problems resulting from Canadian back-off on helicopter research including the question of a replacement for the NAE icing tunnel and Ottawa Spray Rig.
- b) The potential value of a "European HISS".
- c) The value of testing truncated full scale rotor in available icing tunnels should be addressed.
- d) Ongoing exchange of data relating to the correlation of analysis and tests in simulated conditions with natural icing results.
- e) Such other ongoing activities as may be suggested by the symposium suggested above.

6.4.3 A NATO Data Exchange Program to be implemented by the NATO AC/225 Panel X Icing Subgroup to arrange the exchange of data on icing encounters of partially protected helicopters and particularly any problems with mixed conditions, the results of this exchange to be distributed back to the technical community as represented by the proposed Icing Workshop and Facilities Working Group.

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